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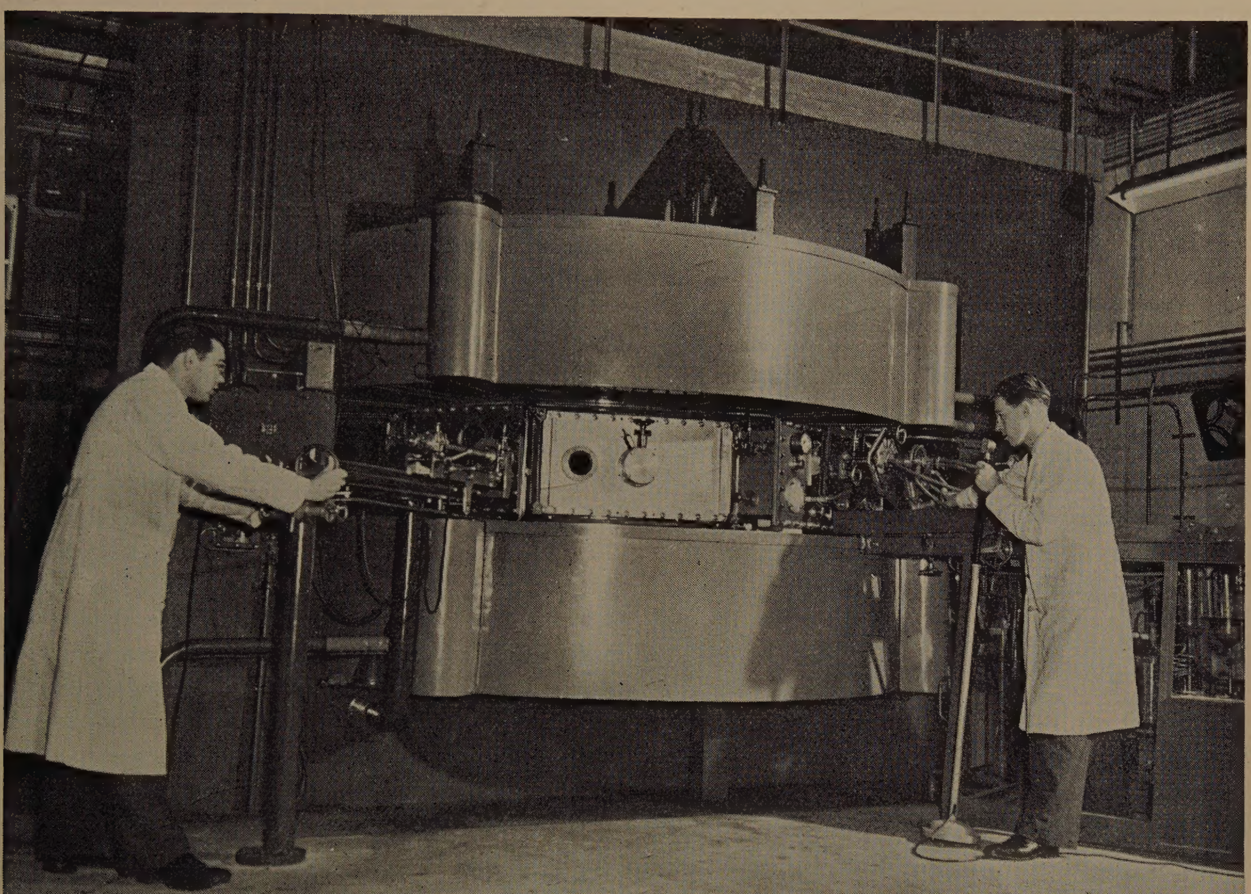

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CYCLOTRON AND SYNCHROCYCLOTRON

by W. de GROOT. 621.384.61

On 10th November 1949, in the Institute for Nuclear-Physical Research at Amsterdam, a synchrocyclotron built by Philips for the said Institute to a design by Prof. Dr. C. J. Bakker and Prof. Dr. Ir. F. A. Heyn was officially taken into use. It is intended to publish a series of articles in this journal describing the construction and working of this apparatus and giving some information about the research work that can be done with it, as also about its further possibilities.

By way of introduction a more general account is given of the working of the cyclotron and the synchrocyclotron, mainly taken from literature already published on this subject.

Introduction

To impart a high velocity and thus a great kinetic energy to a small mass which can travel along a prescribed rectilinear or curved path without friction, a force has to be applied to that mass. The increase ΔT in the kinetic energy T along a part of the path is given by

$$\Delta T = \int K_s \mathrm{d}s, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where K_s is the component of the force along the path and the integration has to be carried out over the part of the path in question. Any component of the force perpendicular to the path and the normal reaction due to the path (which force is likewise perpendicular to the path in the case of frictionless movement) do not perform any work and thus do not contribute towards the increase of T.

Instead of (1) it is sometimes advantageous to use the formula for the increase of momentum (p), which reads:

$$\Delta p = \int K_s \mathrm{d}t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In classical mechanics we have:

$$T = \tfrac{1}{2} M_0 v^2 \,, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$p = M_0 v \,, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where M_0 represents the mass of the particle. Since, however, we shall presently have to deal with particles having a velocity approaching that of light, we shall also have to take into account the changes taking place in the expressions for T and p when v approaches the velocity of light c and thus the quotient v/c, which is always less than unity, becomes of the order of unity. Formulae (1) and (2) then remain valid, but for T and p we get:

$$T = Mc^2 - M_0 c^2 \,, \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$p = Mv \,, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where M_0 now represents the mass of the body at rest and

$$M = \frac{M_0}{\sqrt{1 - v^2/c^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

It is obvious that for $v \ll c$ (5) and (6) become identical with (3) and (4).

The force K may in various ways depend upon the time t or the place s on the path. Let us consider a few cases:

1) An example of the case where K is constant and the particle describes a straight path is, for instance, when a stone is dropped from a high tower.

2) In the case of a projectile shot out of a gun — disregarding the force of gravity — we are concerned with a force K which is very great for a short time and after that zero. Thus the body is given the desired energy in one impulse.

3) One can also imagine the particle being accelerated by a series of impulses at regular distances.

4) In the case of a particle of mass being propelled along a straight path by periodic impulses of short duration, owing to the increasing velocity the distance travelled in the intervals becomes greater and greater; that is to say, the distances measured along the path from point to point where the pulse begins to take effect become longer and longer.

5) All these modes of acceleration can be realized when the particle is caused to describe a curved instead of a straight path for instance by forcing it to travel without friction through a curved channel or like a frictionless bead along a curved wire.

The acceleration of atomic particles

In nuclear physics use is made of light nuclei (protons, deuterons, alpha particles) for bringing about nuclear reactions [1]). Since the nuclear particles acting as projectiles are electrically charged, it is a fairly simple matter to bring accelerating forces to act upon them by subjecting them to the action of electric fields. All cases occurring in the mechanical examples given above are in fact realized in practice.

The acceleration of protons and deuterons by an electric field constant in space and time (analogous to the falling stone) takes place in ion-accelerating tubes for not too high tensions (e.g. 50 to 100 kV).

Acceleration by one short impulse is realized, for example, in the cathode ray tube, in which electrons are accelerated between a cathode and an anode placed close to it, together forming what is called an electron gun, the electrons then travelling on at a uniform velocity. This method of acceleration is also applied to ions, as for instance in the mass spectrograph.

Similar to this is the action taking place in the atoms of a radioactive substance emitting alpha particles. Upon emerging from the nucleus the alpha particle receives an impulse from the repelling Coulomb force of the nucleus and then continues on its way at a uniform velocity until ultimately, retarded by collisions with the molecules of the air, it reaches the end of its track.

As an example of acceleration by short pulses applied at regular distances along the path we may take the action of ion-accelerating tubes for tensions of some hundreds of kilovolts, where for technical reasons the tube is divided into a number of sections, a fraction of the total potential difference being applied to each section.

Acceleration by periodic pulses along a rectilinear

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1) For a general treatise on fundamental nuclear reactions and the part played therein by the particles mentioned, see W. de Groot, Philips Techn. Rev. 2, 97-102, 1937.

2) See, e.g., F. A. Heyn and A. Bouwers, An apparatus for the transmutation of atomic nuclei, Philips Techn. Rev. 6, 46-53, 1941.

path takes place in what is called the linear accelerator, an apparatus which it is not necessary to discuss here.

Finally, acceleration by periodic pulses along a curved path takes place in the cyclotron constructed by Lawrence [3]), the apparatus to which this present article is devoted. The "normal force" required to cause the particle to follow an orbit is derived, in this cyclotron, from a magnetic field: when a particle with mass M and charge Q travels at a velocity v in a direction perpendicular to the lines of force of a magnetic field with induction B it experiences a force K (Lorentz force) perpendicular to v and B given by

$$K = Q\,v\,B\,.$$

The radius of curvature r of the orbit is thereby given, since this force must be equal to the centripetal force required, so that

$$\frac{Mv^2}{r} = Q\,v\,B$$

or

$$Q\,B\,r = M\,v = p \; . \; . \; . \; . \; . \; . \quad (8)$$

If v is comparable to the velocity of light c then M is again given by equation (7).

If B is constant then, with a given velocity v, by (8) we have a circular path, since M is determined only by v. The particles then travel along this circle with an angular velocity

$$\omega = \frac{v}{r} = \frac{QB}{M} \; . \; . \; . \; . \; . \; . \quad (8a)$$

When the particle is accelerated, so that v increases with time, then also r increases and the path described becomes a spiral.

The cyclotron

The cyclotron consists in the main of a magnetic circuit with an "air gap" between the poles (see *fig. 1*). This gap may be of rather considerable dimensions. The distance between the poles is a few decimetres and the cross-sectional diameter of the poles is usually more than 1 metre. Between the poles, which are placed vertically one above the other, forming an airtight joint with them, is a ring of non-magnetic material isolating the gap from the outside air. The cylindrical box-shaped space thus formed is evacuated. Inside this space and supported by insulated rods is a smaller cylindrical box bisected diametrically into two halves

[3]) The first publication on this subject was by E. O. Lawrence and N. E. Edlefsen, Science 72, 376-377, 1930.

each shaped like the capital letter D. That is why these two halves are commonly referred to as the "dees". The gap between the dees is a few cm wide.

Between the dees, which together form a sort of capacitor, an alternating voltage of some tens of kV is applied with a frequency in the order

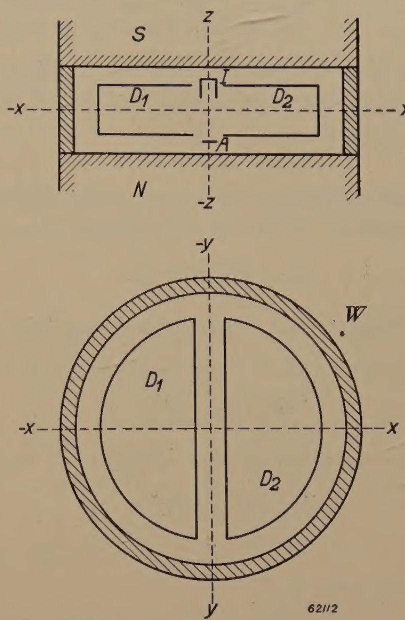

Fig. 1. The acceleration chamber of the cyclotron (drawn schematically). N and S the two poles of the magnet, W the wall of the vacuum chamber, D_1D_2 the two "dees", I ion source (in which is a filament), A anode for picking up the electrons coming from the source.

of 10^7 c/s. As a result an approximately horizontal, homogeneous, electric alternating field is formed in the gap between the dees, while the remaining space inside the dees is practically free of any field. In addition, everywhere in the gap there is a constant and practically homogeneous magnetic field with induction B of about 1.5 Wb/m². In the centre of the gap, slightly above the horizontal plane of symmetry, is an ion source by means of which deuterons, for instance, can be injected into the vacuum at a low velocity.

Let the electric field between the dees be

$$E = E_{\rm m} \cos \omega_E t\,,$$

with ω_E given a very definite value such, as will presently be explained, as to equal the aforementioned angular velocity of the particles, i.e., for not too high velocities, where $M = M_0$, a value:

$$\omega_E = \frac{QB}{M_0}.$$

Let us consider a particle at rest in the field. This will be given momentum by the field and as soon

as it reaches a certain velocity the Lorentz force comes into action, thereby causing the particle to describe a sort of spiral path lying for the moment in the gap between the dees. The shape of this path depends to some extent upon the initial conditions, in particular upon the moment at which the particle (with velocity zero) is released into the field.

After a few loops, however, a situation arises where the particle lies approximately in the middle of the gap at the moment that the field is at its maximum and where the radius vector r of the orbit increases proportionately with t.

The differential equations for a particle with charge Q and mass M_0 in a horizontal electric alternating field

$$E_x = E_m \cos \omega_E t ,$$

combined with a vertical, homogeneous, magnetic field B_z, where

$$\omega_E = \frac{Q}{M_0} B_z ,$$

are, with the coordinates indicated in fig. 1:

$$M_0 \ddot{x} = Q(E_x - B_z \dot{y}) ,$$
$$M_0 \ddot{y} = QB_z \dot{x} ,$$

or, omitting the index E,

$$\ddot{x} = (QE_m/M_0) \cos \omega t - \omega \dot{y} ,$$
$$\ddot{y} = \omega \dot{x} .$$

The solution for a particle released into the field at a moment $t = \tau$ (with $x = y = 0$ and $\dot{x} = \dot{y} = 0$ for $t = \tau$) is:

$$x = \frac{QE_m}{2 M_0 \omega^2} \left[- \sin \omega\tau \sin \omega (t-\tau) + \omega (t-\tau) \sin \omega t\right] ,$$

$$y = \frac{QE_m}{2 M_0 \omega^2} \left[- \cos \omega\tau \sin \omega (t-\tau) + 2 \sin \omega\tau \,(1 - \cos \omega (t-\tau)) + \omega (t-\tau) \cos \omega t\right].$$

These equations represent a sort of spiral the shape of which depends to a certain extent upon the parameter τ. After the particle has travelled one single loop $\omega(t-\tau) \gg 1$ and it is mainly the last terms that are of importance. If, for instance, $\omega(t-\tau) = 2\pi$, $E_m = 10^6$ V/m and $B_z = 1.5$ Wb/m², then for a deuteron ($\omega = 7 \times 10^7$ rad/sec) the radius vector $r = (x^2 + y^2)^{1/2}$ is equal to $\pi Q E_m / M_0 \omega^2 = \pi E_m / \omega B_z \approx 3$ cm.

Owing to the increase of r the particle soon penetrates into the field-free space inside the dees. From that moment onwards it is accelerated only during the periods of time when it traverses the gap. In the interim period it describes semi-circular paths with a constant velocity, with a slightly larger radius each time.

The time taken to describe such a semi-circle is: $\pi r/v = \pi M_0/QB = \pi/\omega_E$. From the value chosen for ω_E it follows that once the particle is made to traverse the gap at the moment that the field is at its maximum it will continue to do so even though the radius of the orbit increases each time; to put it in other words, the particle is in resonance with the electric field.

Each time the particle traverses the gap its energy increases by a constant amount ΔT. According to formula (3) therefore v^2 is proportional to the number of loops and, since v is proportional to r, the radius of the spiral increases further in proportion to $\sqrt{t}$, so that the wider the turns of the spiral the closer they will lie together.

The greatest value that the radius can assume is determined by the radius R of the dees. When this is reached then, for an ion with charge $Q = Ze$ — where e represents the elementary charge ($= 1.6 \times 10^{-19}$ coulomb) and Z the charge number of the ion (for light ions equal to the nuclear charge) — the energy is:

$$T_{\max} = \tfrac{1}{2} M_0 v^2 = \tfrac{1}{2} M_0 \left(\frac{RQB}{M_0}\right)^2 = \frac{Z^2 e^2}{M_0} \cdot \frac{R^2 B^2}{2} .$$

Since

$$M_0 \approx A\, M_H ,$$

where M_H represents the proton mass and A the atomic weight, and expressing the energy in electron volts, it is found that with $T_{\max} = eV_{\max}$:

$$V_{\max} = \frac{Z^2}{A} \cdot \frac{e}{M_H} \cdot \frac{R^2 B^2}{2} .$$

If, for instance, $R = 0.5$ m and $B = 1.5$ Wb/m² then, since $e/M_H \approx 10^8$ coulombs/kg, we have:

$$V_{\max} \approx 3 \cdot 10^7 \frac{Z^2}{A} \text{ volts} = 30 \frac{Z^2}{A} \text{ megavolts.}$$

For protons $Z = 1$ and $A = 1$, whilst for deuterons $Z = 1$, $A = 2$ and for alpha particles $Z = 2$, $A = 4$. Thus in the case considered here the maximum energy for deuterons is about 15 MeV and for protons and alpha particles 30 MeV.

These figures, however, are only of value for the order of magnitude, because, as will presently be shown, there are other factors affecting the maximum energy attainable.

Electric and magnetic focusing

It has been assumed above that the electric field between the dees is homogeneous and that the electric force is parallel to the horizontal plane of symmetry of the system. A particle released with zero velocity will then begin to move in a direction which is also parallel to that horizontal plane. This, however, is all only very approximately true. Actually the electric equipotential planes penetrate somewhat into the space inside the dees and the

electric lines of force are as a result curved. *Fig. 2* illustrates this effect. One of the consequences of this is that those particles which do not start exactly in the central plane receive momentum in the vertical direction and soon reach the top or bottom walls of the dees.

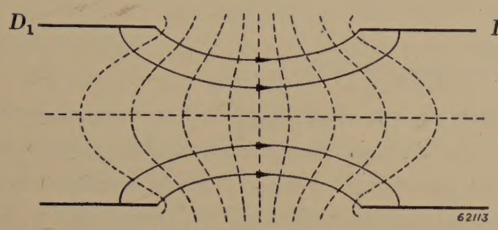

Fig. 2. The electric field between the dees.

The inhomogeneity of the electric field is of importance also during the further process of acceleration, but on the whole this influence is favourable, since the field appears to have a concentrating action, drawing back to the horizontal plane of symmetry such particles as, through some cause or other, have received a velocity component leading them away from that plane [4] [5]). This is due to two causes. In the first place, owing to their velocity increasing in the field, the particles are subjected to diverging forces (on the right in fig. 2 if the particle comes from the left) for a shorter time than they are exposed to converging forces (on the left in fig. 2), and moreover many particles pass through the field while it is already beginning to decrease, thus assisting the converging action.

Since the influence of the field upon the electrons is comparable to that of a lens upon a beam of light rays one speaks of electric "focusing". This focusing action diminishes as the velocity of the particle increases, ceasing when $r \approx {}^1/_3\, R$.

Fortunately a second focusing then comes into action, namely the magnetic focusing. Owing to the spread of the magnetic field there is a small decrease in the strength of that field from the centre outwards as a result of which the lines of force curve slightly outwards (*fig. 3*) and consequently the Lorentz force at points outside the centre plane has a component perpendicular to and directed towards that plane. Thus the particle is subjected to a force proportional to the distance from the plane of symmetry and begins to oscillate about the ideal path situated in that plane with a frequency which, as a further calculation shows, is given by:

$$\omega_{\mathrm{vert}} = \omega_E \sqrt{n},$$

where $n = -\mathrm{d} \log_e B_z / \mathrm{d} \log_e r$.

[4]) M. E. Rose, Phys. Rev. **53**, 392-408, 1938.
[5]) R. R. Wilson, Phys. Rev. **53**, 408-420, 1938.

There is also a horizontal magnetic focusing action: particles which, for some reason or other (e.g. owing to collisions with gas molecules), have either a direction of velocity or a radius vector differing from that of the ideal path are automatically attracted towards the ideal path again. This, too, is accompanied by oscillations, with a frequency

$$\omega_{\mathrm{hor}} = \omega_E \sqrt{1-n} .$$

The existence of "vertical stability" can be proved as follows [6]). If z is the distance from the horizontal plane of symmetry then

$$M_0\, \ddot{z} = Q v B_r ,$$

where B_r represents the radial component of the induction.

In the gap, according to Maxwell's equations:

$$\frac{\partial B_z}{\partial r} - \frac{\partial B_r}{\partial z} = 0.$$

Now in the plane of symmetry $B_r = 0$ and $z = 0$. Hence $\partial B_r/\partial z$ is to a first approximation equal to B_r/z, so that

$$B_r = z \frac{\partial B_z}{\partial r} .$$

This gives:

$$\ddot{z} = \frac{Q\omega}{M_0 r} z \frac{\partial B_z}{\partial r} ,$$

and since $QB/M_0 = \omega \approx \omega_E$:

$$\ddot{z} + \omega_E^2 z \frac{r}{B_z} \frac{\partial B_z}{\partial r} = 0 ,$$

or:

$$\ddot{z} + \omega_E^2 n z = 0 .$$

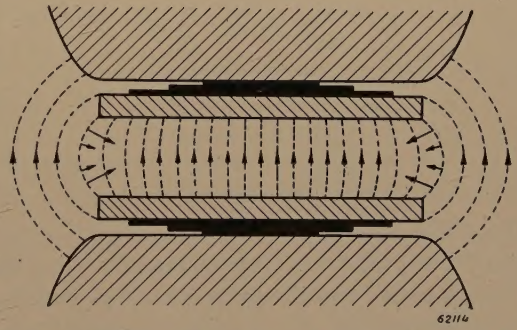

Fig. 3. The magnetic field of the cyclotron with lines of force curved outwards (dotted lines). The strength of the field diminishes slightly from the centre outwards. The direction of the Lorentz force at the edge is indicated by small arrows.

This represents an oscillation with the frequency $\omega_E \sqrt{n}$. In a similar way the existence can be proved of radial stability with the frequency $\omega_E \sqrt{1-n}$.

If $n = 0.2$ then $\omega_{\mathrm{hor}} = 2\omega_{\mathrm{vert}}$. Closer investigation shows that a sort of resonance then arises, accompanied by transmission of energy between the two modes of oscillation and resulting in considerable widening of the path and consequent defocusing. That is why care has to be taken to ensure that

[6]) D. W. Kerst and R. Serber, Phys. Rev. **60**, 53 58, 1941. See also A. Bierman and H. A. Oele, Betatrons with and without iron yoke, Philips Techn. Rev. **11**, 65-78, 1949, No. 3.

the fraction n, which has to be as small as possible with a view to keeping the particles "in step", does not exceed the value 0.2. The radial variation of B_z and thus the magnitude of n can be altered by providing an additional air gap and partly filling this with circular iron plates ("shims") of different diameter (see fig. 3). It can be so arranged, for instance, that in the centre B_z decreases with the square of r and farther away from the centre linearly with r. In this way the above condition for n can be satisfied in practically the whole of the accelerating space ($0 < r < R$).

Limitations of the classical cyclotron

According to the theory outlined above the energy of the particles could be increased indefinitely by increasing the radius R of the dees. Increasing B would have the same effect but then, of course, one is confined to material limits.

Actually there are other natural limits for the highest energy attainable. In the first place, for the magnetic focusing it is essential that the field diminishes outwards. In the second place, according to (5) the quantity M increases with increasing energy. As a result of these causes the quantity $\omega = QB/M$, i.e. the value the electric angular frequency should have for exact resonance of the particles circling with the electric field, diminishes as the velocity increases, thus as the radius of the orbit becomes larger.

Eliminating v from the equations (7) and (8a) we find ω and M as functions of r, viz.:

$$\frac{1}{\omega^2} = \left(\frac{M_0}{QB}\right)^2 + \frac{r^2}{c^2},$$

$$M^2 = M_0^2 + \left(\frac{QBr}{c}\right)^2.$$

If $\omega_{r=0} = \omega_E$ is the constant frequency of the electric field then at the edge of the gap ω_E will be greater than $\omega(r)$.

As a result, with a certain value of r the particle will travel rather too slowly and next time pass the gap a little too late. If this effect accumulates the particle will ultimately reach the gap at a moment when the electric field is zero or even of opposite polarity, so that it no longer has an accelerating action and may even decelerate the particle, the energy no longer increasing but even possibly decreasing.

This can be remedied by giving ω_E a value in between $\omega_{r=0}$ and $\omega_{r=R}$, and further by giving the electric field between the dees the largest possible amplitude, so that the acceleration each time the particle passes through the field is as great as possible and the number of loops that have to be travelled to reach a certain energy is as small as possible, while the particle "loses step" as little as possible.

Calculations show that with an amplitude of some hundreds of kV between the dees it is possible in this way, with a reasonable yield, to accelerate protons up to 15 MeV, deuterons up to 25 MeV and alpha particles up to 50 MeV (see the article quoted in footnote [4])). This, however, is the limit for the "classical" cyclotron.

The synchrocyclotron

When, about 1930, E. O. Lawrence conceived the cyclotron (see the article quoted in footnote [3])), thereby basing the design on the resonance formula $\omega_E = QB/M_0$, and decided to construct such an apparatus, it was not a priori certain that he would succeed in getting particles of great energy with reasonable efficiency. However, fortune favours the bold, and fortune here was in the form of the electric and magnetic focusing, thanks to which a practical application of the idea first became possible.

It has been seen, however, that by the very reason of B_z decreasing with increasing r — which condition is essential for magnetic focusing — and moreover owing to M increasing with increasing T, it is impossible to fulfil the resonance condition exactly and that this sets a limit to the highest energy attainable.

Now, theoretically, there is a simple means of meeting this, namely by making the frequency ω_E of the electric field variable instead of leaving it constant, so that the condition $\omega_E = QB_z/M$ will always be valid while the particle is describing its spiral.

Again it is not a priori certain that this principle can be successfully applied with a high efficiency. It could be argued that this condition can only be fulfilled for one particle at a time, namely for the particle that starts off just at the right moment, and not for particles starting a little earlier or later. Furthermore, it seems difficult to "modulate" the frequency ω_E in such a way that the condition $\omega_E = QB_z/M$ is always exactly fulfilled along the whole of the orbit.

Here too, however, there is a fortunate circumstance which makes it possible to apply successfully the principle published almost simultaneously in 1945 by Veksler and by Mc Millan [7]), and which, moreover, relieves us of the necessity to make ω_E dependent upon time in a prescribed manner.

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[7]) V. Veksler, J. Phys. U.S.S.R. **9**, 153, 1945; E. M. Mc Millan, Phys. Rev. **68**, 443L, 1945. — An analogous proposition was made by Oliphant in 1943, but not published until 1947: M. L. Oliphant, J. S. Gooden and G. S. Hide, Proc. Phys. Soc. **59**, 666, 1947.

To make this clearly understood let us once more assume that ω_E is constant and that there is a radius vector r for which

$$\omega_E = \omega(r) = \frac{v(r)}{r} = \frac{QB(r)}{M} \quad . \; . \; . \quad (9)$$

Imagine that there is a particle travelling along this circular path and passing the gap between the dees each time at the moment at which the electric field is zero and changing from an accelerating to a decelerating field. Let us say that such a particle has a phase $\varphi = 0$ with respect to the field.

It is obvious that since its energy T does not change this particle can continue travelling along this orbit for an indefinite length of time. Now imagine a particle describing the same orbit but such that at the moment when the field is zero its azimuth with respect to the gap has a value φ_1. Each time this particle traverses the gap the field will have an accelerating action. Therefore, each time it passes the gap it will be accelerated, the energy T thereby increasing, so that automatically the radius r of the orbit is increased and the looping frequency reduced. Thus the particle will reach the gap a little later each time until it again has a phase $\varphi = 0$ with respect to the field. Then, however, it will no longer satisfy equation (9), because its ω is then smaller than ω_E and thus the particle still travels too slowly.

The process therefore continues in this way: in course of time the particle will come to pass the field at a moment when it has a retarding action, as a consequence of which its energy diminishes and thus r decreases and $\omega(r)$ again becomes greater. Ultimately it once more arrives in its old orbit with the right $\omega(=\omega_E)$ but now with a negative phase, exactly opposed to the phase φ_1 with which it started ($\varphi = -\varphi_1$). The process is then repeated in the reverse direction, the phase increases (thus decreasing in absolute value), ω increases, while T decreases. When, as a result of this, φ has again become zero we still find $\omega > \omega_E$. Thus the increase of φ continues further, accompanied by a decrease of ω and increase of T. When ultimately the particle has again arrived in its old orbit it once more has the phase φ_1 with which it started and the original values of ω and T. This cycle is repeated for an indefinite length of time and we thus see a sort of vibration set in whereby the phase oscillates between φ_1 and $-\varphi_1$ while at the same time T, ω and r fluctuate about a mean value.

Thus there is a certain stability (phase stability) with respect to the orbit determined by (9). This stability is maintained up to very large values of φ_1, namely up to $\varphi_1 = \pm\,\pi$.

Let us now imagine the same process taking place while ω_E is not constant but gradually diminishing.

A particle that is describing an orbit whereby $\omega = \omega_E$ but which passes the gap at the moment when the field is accelerating (thus φ is not zero but positive) will increase or decrease in phase as ω_E becomes smaller. This depends upon whether the decrease of ω, accompanied by the increase of T, is greater or less than the decrease of ω_E. One can therefore imagine that there is a particle with such a phase ($\varphi = \varphi_s$) that for this particle ω always equals ω_E. This particle will continually be accelerated and will always be synchronous with the field (it is from this synchronism that the name synchrocyclotron has been derived). It can, however, also be proved that particles whose phase at a certain moment is not equal to φ_s and for which at that moment ω is not equal to ω_E will start oscillating about the expanding "synchronous" orbit and thus on the average be accelerated just as much, provided $|\omega - \omega_E|$ and $|\varphi - \varphi_s|$ remain confined within certain limits.

From the foregoing it follows that when $\varphi = \varphi_s$ and $\omega = \omega_E$, then $\mathrm{d}\varphi/\mathrm{d}t = 0$. It is obvious that in general $\mathrm{d}\varphi/\mathrm{d}t = \omega - \omega_E$ and thus $\mathrm{d}^2\varphi/\mathrm{d}t^2 = \mathrm{d}\omega/\mathrm{d}t - \mathrm{d}\omega_E/\mathrm{d}t$, in which the differentiation process has to be carried out such that $\mathrm{d}t$ does not diminish to zero but remains great enough for at least one loop to be completed in the time $\mathrm{d}t$. With this assumption the differential equation for φ reads [8]):

$$\frac{\mathrm{d}^2\varphi}{\mathrm{d}t^2} = C\,(\sin\varphi_s - \sin\varphi) \quad . \; . \; . \; . \; . \; . \quad (10)$$

where

$$C \sin\varphi = -\,\mathrm{d}\omega/\mathrm{d}t \quad . \; . \; . \; . \; . \; . \; . \; . \quad (11)$$

and

$$C \sin\varphi_s = -\,\mathrm{d}\omega_E/\mathrm{d}t \quad . \; . \; . \; . \; . \; . \; . \; . \quad (12)$$

Equation (10) is the same as that for a mathematical pendulum upon which, in addition to the usual "gravitation couple" $-C \sin\varphi$, a constant couple $C \sin\varphi_s$ is acting (see *fig. 4*). If $\varphi_s = 0$ (ω_E = const.) then φ fluctuates about the value $\varphi = 0$ between $+\varphi_1$ and $-\varphi_1$, with $|\varphi_1| < \pi$. If $\varphi_s \neq 0$ then the state of equilibrium is $\varphi = \varphi_s$ and φ may fluctuate between φ_1 and φ_2, where $\varphi_s \leqq \varphi_1 \leqq \pi - \varphi_s$, whilst $-(\pi - a) \leqq \varphi_2 \leqq \varphi_s$. a increases with increasing $\varphi_s (a > 2\varphi_s)$.

In the case of the cyclotron C and φ_s, strictly speaking, are functions of r, just like B, ω and T. Instead of (11) one can in fact also write:

$$C \sin\varphi = -\frac{\mathrm{d}\omega}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{\mathrm{d}\omega}{\mathrm{d}T} \cdot 2eV \sin\varphi \cdot \frac{\omega}{2\pi},$$

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[8]) D. Bohm and L. Foldy, Phys. Rev. **70**, 249-258, 1946; **72**, 649-661, 1947. In these articles the energy gain per revolution is taken as being equal to $eV \sin\varphi$. In the present article $2eV \sin\varphi$ has been taken, where V represents the maximum potential difference between the dees and account has been taken of the fact that the particle traverses the gap twice in every revolution.

hence:

$$C = -\frac{\mathrm{d}\omega}{\mathrm{d}T} \cdot 2eV \cdot \frac{\omega}{2\pi}.$$

The variation of C with r however is not so great (10-20%) as to invalidate the truth of the following argument where C is regarded as a constant.

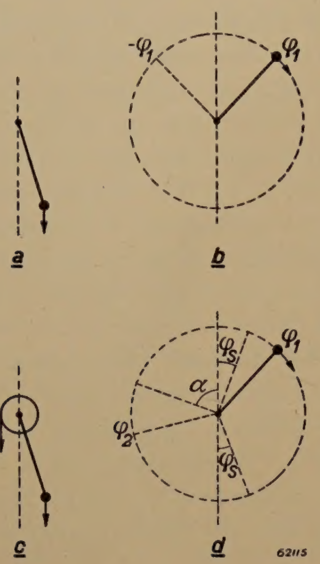

Fig. 4. Diagrammatic drawing of a mathematical pendulum behaving according to formula (10).
a) and *b*) $\varphi_s = 0$, the ordinary mathematical pendulum, extreme positions $+\varphi_1$ and $-\varphi_1$, whereby $|\varphi_1| < \pi$.
c) and *d*) pendulum with constant couple $C \sin \varphi_s$, extreme positions φ_1 and φ_2, whereby $\varphi_s \leqq \varphi \leqq \pi - \varphi_s$ and φ_2 lies between φ_s and $-(\pi - \alpha)$, $(\alpha > 2\varphi_s)$.

From (12) it follows that $-\mathrm{d}\omega_E/\mathrm{d}t$ may not be greater than C, as otherwise it is impossible to have a synchronous path. The more C differs from $-\mathrm{d}\omega_E/\mathrm{d}t$ the larger is the group of particles "taken along". But $-\mathrm{d}\omega_E/\mathrm{d}t$ may not be too small either, because then, owing to the phase oscillation, a large number of particles tend to return to the starting point and are lost as far as the acceleration is concerned. It must be borne in mind that, as already shown, almost all the particles begin with a phase $\varphi = \pi/2$, where $\dot{\varphi}$ may be either greater or less than 0 according to whether, at the moment that the particle starts off, $\omega_{r=0}$ is greater or less than the instantaneous value of ω_E. Thus there is an optimum value for $-\mathrm{d}\omega_E/\mathrm{d}t$, and at that value the portion of all particles carried along is as large as possible.

Actually the frequency ω_E is "modulated" by connecting to the oscillator supplying that frequency a variable capacitor the capacitance of which is a periodical function of time, with a cycle that is large compared with the time taken by a particle to complete one orbit.

As a function of t, therefore, ω_E increases and decreases alternately, and only those intervals of time in which ω_E decreases are useful for the acceleration. Due to the phase stability, however, not one particle but a whole group of particles benefits from the favourable conditions. In practice this group comprises, say, 1% of the total number of particles, so that 99% of the ions produced are lost for the acceleration. With the synchrocyclotron this adverse factor has to be taken into account. On the other hand there is the favourable factor of being able to increase the energy output.

Another advantage of the method described is that — since there is no fear of the particle getting out of phase with respect to the field — there is no imperative need to ensure that the number of "loops" required to obtain a certain energy is as small as possible. That is why, in the synchrocyclotron, the voltage between the dees need not be so high as in the case of the classical cyclotron, a factor that has a number of practical advantages in connection with insulation and the risk of sparking. In particular, less stringent requirements have to be met as regards the vacuum, thus allowing of a large production of ions in the centre.

Summary. Following upon an introduction on the acceleration of particles as a mechanical problem, a description is given of the functioning of a cyclotron in which light nuclei, such as protons, deuterons or alpha particles, can be accelerated up to an energy of some tens of millions of electron volts. A limit is set to the energy attainable by the fact that, owing to the magnetic induction decreasing and the mass increasing for velocities comparable to the velocity of light, at the edge of the field the resonance condition is no longer fulfilled. It is then indicated how, in the synchrocyclotron, by modulating the frequency of the accelerating field the resonance condition can, on an average, be fulfilled right up to the edge of the field, at least for a portion of the particles. As a result, be it at the cost of efficiency, particles can be obtained with very much higher energies than are possible with the classical cyclotron.

AN EXPERIMENTAL "STROBOSCOPIC" OSCILLOSCOPE FOR FREQUENCIES UP TO ABOUT 50 Mc/s

II. ELECTRICAL BUILD-UP

by J. M. L. JANSSEN and A. J. MICHELS.

621.317.755:621.3.029.5/.6

From the fundamental principles of the stroboscopic oscilloscope dealt with in a previous article, to the actual building of an instrument is a big step. The generation of extremely short voltage pulses, the synchronization of those pulses, the construction of the connecting cables and of the variable attenuators for the input voltages are only a few of the problems encountered in the practical execution of this oscilloscope. This second article shows how these problems have been solved.

In a previous article [1]) it was shown how, in principle, an A.F. image of an H.F. voltage v_0 can be obtained by causing the latter to be scanned by electrical pulses modulated in phase. We had arrived at a block diagram which is reproduced here (*fig. 1*) but which, as will presently be seen, needs some additional details.

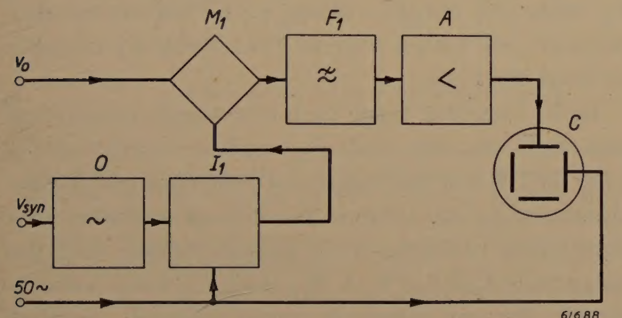

Fig. 1. Simplified block diagram of a stroboscopic oscilloscope. v_0 H.F. voltage to be examined, M_1 mixing circuit, F_1 low-pass filter, A A.F. amplifier, C cathode ray tube, I_1 pulse generator, O synchronizing oscillator, v_{syn} synchronizing voltage (synchronous with v_0). The mains voltage (50 c/s) provides both for the phase modulation of the pulses and for the horizontal deflection of the electron beam.

Recapitulating some of the results arrived at in article I, the functioning of the oscilloscope may be described as follows:

The voltage v_0 is mixed, in a mixing valve M_1, with pulses derived from a generator I_1. The H.F.-components are removed from the output voltage of the mixer by a filter F_1, and the signal is then amplified by an A.F. amplifier A and applied to the horizontal deflection plates of a cathode ray tube C. The frequency of the pulse generator is controlled by an oscillator O, which in turn is synchronized by an externally applied synchronization voltage v_{syn} which has to be synchronous with v_0. In this way a multiple of the repetition frequency f_i of the pulse is made equal to the fundamental frequency f_0 of v_0; as found by calculation in article I, a favourable value for f_i is about 100,000 c/s. The pulses are phase-modulated (preferably sinusoidally) with a frequency ν, which should be chosen as low as possible so as to be able to include in the image as many harmonics of v_0 as possible; the mains frequency is used here (ν = 50 c/s). By arranging for the horizontal deflection to take place synchronously with the phase modulation (thus likewise with the mains frequency) a stationary picture is obtained with a linear time scale.

After a brief description of the mixing stage, the filter and the A.F. amplifier, we shall have to describe the pulse generator and its synchronization more fully. Next comes the electronic switch, by means of which two oscillograms can be produced simultaneously, and finally the connecting cables and the construction of the variable attenuators will be dealt with.

It is emphasized that these descriptions refer to an e x p e r i m e n t a l model of the oscillograph, the primary object of which was to put the fundamental theory of the stroboscopic method to a practical test. In tackling the problems encountered no attempt has been made to find the best solution, the only choice being the design which involved the least development work. When dealing with some of the points we shall have occasion to recall this to mind.

The mixing stage

The main elements of the mixing stage are represented in *fig. 2*. The mixing valve is a pentode EF 50.

[1]) J. M. L. Janssen, An experimental "stroboscopic" oscilloscope for frequencies up to about 50 Mc/s, I. Fundamentals, Philips Techn. Rev. 12, 52-59, 1950 (No. 2), here further referred to as article I.

The voltage v_0 to be examined is applied to the control grid and the pulses are fed to the anode. As can be seen, the anode does not receive a positive high tension but a small negative direct voltage (of a few volts) derived from the cathode resistance. The object of this is fully to suppress the anode current in between the pulses, so that the mixing stage is made insensitive for hum voltages and any other interference. The screen grid does receive the usual positive voltage (180 V), which is kept constant by two stabilizing tubes connected in series. It appears to be an advantage to give also the suppressor grid a positive voltage (about 100 volts), for then the conversion conductance is much greater and smaller anode-voltage pulses are needed (15 V amplitude) than when the voltage of the suppressor grid was zero. That is why this grid has been connected to the common point of the stabilizing tubes.

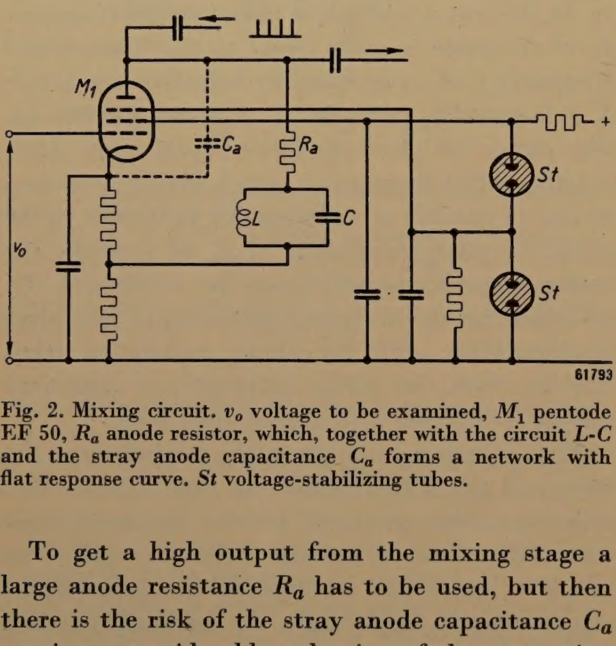

Fig. 2. Mixing circuit. v_0 voltage to be examined, M_1 pentode EF 50, R_a anode resistor, which, together with the circuit L-C and the stray anode capacitance C_a forms a network with flat response curve. St voltage-stabilizing tubes.

To get a high output from the mixing stage a large anode resistance R_a has to be used, but then there is the risk of the stray anode capacitance C_a causing a considerable reduction of the conversion gain at frequencies still below the cut-off frequency of the low-pass filter, which follows the mixing stage. (As calculated in I, this cut-off frequency has to be lower than $\frac{1}{2}f_i \approx 50{,}000$ c/s; in this experimental apparatus we have chosen 40,000 c/s.) Such a falling frequency characteristic would lead to an erroneous reproduction of the v_0 curve. To keep this characteristic horizontal up to 40,000 c/s the well-known method was chosen of connecting in series with the anode resistor R_a an inductor L and a capacitor C in parallel (fig. 2).

The filter and the A.F. amplifier

For the filter we have chosen a simple ladder network with a capacitance in each of the parallel branches and an inductor shunted by a capacitor in each of the series branches. Such a filter has the property that for frequencies above about 50% of the cut-off frequency the transmission is not entirely faithful in phase, with the result that high harmonics of the v_o curve are not exactly reproduced in the right phase relations in the oscillogram. Filter circuits exist (with mutual inductances between the filter stages) which are faithful in phase up to about 85% of the cut-off frequency, but such a complicated filter has not been used in the experimental apparatus.

Following the filter is a push-pull stage (double pentode EFF 51) which with an asymmetrical input (earthed on one side) produces a symmetrical output voltage used for the vertical deflection in the cathode ray tube.

The pulse generator

Differentiating network

There are various ways of generating pulses. For our purpose we have chosen the method whereby the pulses required for the scanning are obtained by using the output voltage of a "differentiating" network fed with a current that suddenly changes at fixed intervals.

In its simplest form such a network consists of two resistors, R_1 and R_2, and a capacitor C_m (*fig. 3a*). When the supply current changes discontinuously by an amount I_0 there is a similar discontinuous variation of the output voltage with the magnitude $I_0R_1R_2/(R_1+R_2)$, since C_m forms a short-circuit for an infinitely rapid change, so that R_1 and R_2 are in parallel at the moment of the sudden change. When, after the sudden change, the input current remains constant then the output voltage v changes according to the expression:

$$v = I_0 \frac{R_1R_2}{R_1+R_2} \cdot \exp\left\{-\frac{t}{(R_1+R_2)\,C_m}\right\}.$$

Thus the shape of this voltage pulse, and also its frequency spectrum, is determined by the product $(R_1+R_2)C_m$. If a particular frequency spectrum is specified and a given value is chosen for C_m, then the value of R_1+R_2 is fixed. The amplitude of v is then proportional to R_1R_2 and thus is a maximum when $R_1 = R_2$. This maximum becomes greater as C_m is reduced, while keeping $(R_1+R_2)C_m$ constant.

It would therefore be expected that by a suitable choice of C_m or $(R_1+R_2)C_m$, pulses could be generated of any amplitude or width. However, no allowance has yet been made for the inevitable stray

capacitances (C_1, C_2, fig. 3*b*) parallel to R_1 and R_2. These capacitances prevent the voltages at R_1 and R_2 from changing discontinuously, the effect being apparent when $(R_1 + R_2)C_m$ becomes of the same order as the time constants R_1C_1 and R_2C_2. This has the effect of widening the pulse and reducing its amplitude.

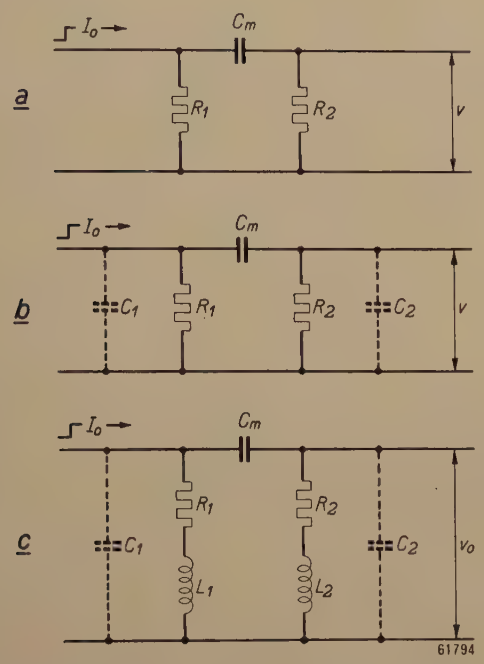

Fig. 3. Differentiating networks. *a*) When the input current is caused to make a step I_o a voltage pulse v arises across the resistor R_2. The coupling capacitance is C_m. *b*) As in (*a*) but with the stray capacitances C_1 and C_2. *c*) To improve the waveform of the pulse the inductors L_1, L_2 are connected in series with R_1 and R_2 respectively.

This effect is of such a nature that for generating pulses as are needed with a stroboscopic oscilloscope for frequencies up to 50 Mc/s — pulses with an amplitude of at least 15 V and a width in the order of at most 10^{-8} s — such simple networks as those of figs. 3*a* and 3*b* are unsuitable. It is possible to counteract the effect of the stray capacitances in the same way as in resistance-coupled amplifiers, by connecting inductors in series with the resistors (fig. 3*c*). Two resonance circuits are then obtained, coupled by the capacitor C_m. Such a system has two characteristic frequencies, both of which are excited when a current surge is sent through one of the circuits. The voltage across the other circuit is then the superposition of two damped oscillations v' and v'', each with one of the characteristic frequencies. It is possible, by a suitable choice of the network elements, to get a situation as follows (*fig. 4*): at the time of the first positive peak of the oscillation with the highest frequency (v' in fig. 4) the other oscillation (v'') is likewise positive, while at the time of the second positive peak of v' the oscillation v'' is negative; owing to the damping the amplitudes of the next peaks are negligible. The negative peaks are of no consequence here. Thus the output voltage $v = v' + v''$ (fully-drawn line in fig. 4) consists mainly of one positive pulse (roughly in the shape of half a sine wave).

Denoting the "average" width of the pulse [2]) by τ ($\approx {}^2/_3$ of the base width) then, as a calculation shows, for the amplitude V_{max} we have approximately:

$$V_{max} \approx \frac{1}{\pi} \cdot \frac{\tau I_0}{C_1 + C_2} .$$

Substituting for V_{max} and τ the values mentioned, viz. 15 V and 10^{-8} s, and for C_1 and C_2 the values that occur in practice (C_1 = 15 pF, C_2 = 7.5 pF), it is found that the sudden change of the current must be about 100 mA. In practice a higher value proves to be necessary (about 200 mA), partly for the following reason.

So far it has been assumed that the change of the input current is absolutely discontinuous. In point of fact, however, it takes some finite time, with the result that the voltage pulse is wider and also lower than would be the case in the event of an absolute discontinuity. This effect becomes of particular importance as soon as the time taken for the current change becomes of the same order as the permissible duration of the pulse τ.

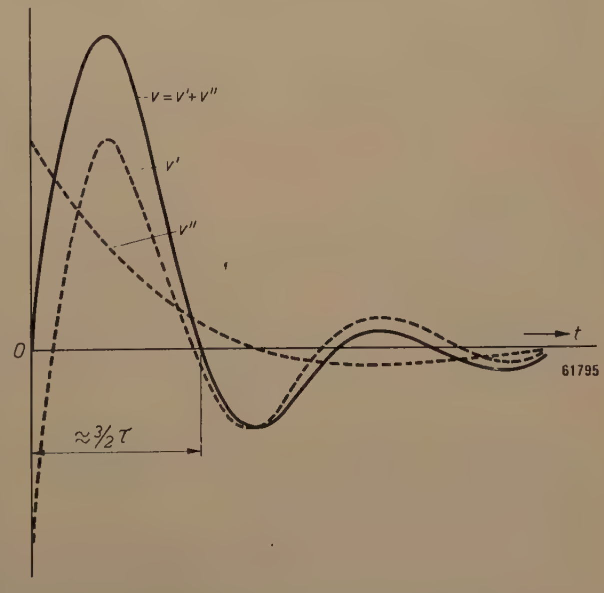

Fig. 4. The output voltage v, as function of the time t, of the network according to fig. 3*c* when a sudden current change occurs at the input. The voltage v is the sum of two characteristic oscillations, v' and v''.

[2]) See I, page 58.

Circuit for producing the sudden current change

This leads up to the question how the change in current can be brought about quickly enough. It is obvious that the differentiating network should be incorporated in the anode circuit of an amplifying valve (P_1, *fig.* 5) and a voltage applied to the control grid of that valve with a curve of such a form that the anode current is suddenly interrupted periodically. Owing to the large anode-current pulses required, the amplifying valve should be an output valve; the type EL 6 for instance can easily produce surges of 200 mA, provided the mean value of the anode current is not too high. This condition can be fulfilled by giving the grid voltage curve a form as represented in *fig.* 6*a*; the corresponding anode current variation and the form of the pulses supplied by the network are sketched in figs. 6*b* and 6*c* respectively. The manner in which this grid voltage is obtained will be explained in the next section.

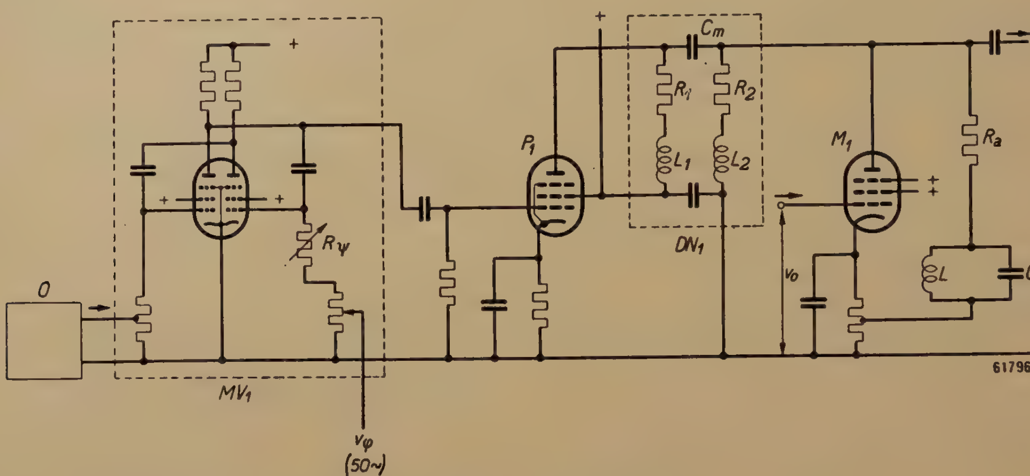

Fig. 5. The pulse generator I_1 (fig. 1) consists of a multivibrator MV_1, an output valve P_1 and a differentiating network DN_1 according to fig. 3*c*. *O* is the synchronizing oscillator. M_1, with R_a, *L* and *C*, forms the mixing circuit according to fig. 2. The mean position of the pulse can be adjusted with the resistor R_ψ. The voltage v_φ provides for the phase modulation. The valve in the multivibrator is a double pentode EFF 51, P_1 is an EL 6 valve.

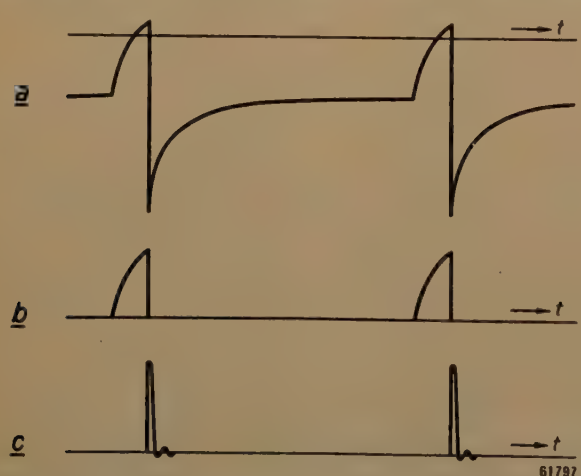

Fig. 6. Plotted as a function of the time *t*: *a*) the voltage on the control grid of the valve P_1 (fig. 5), (*b*) the anode current of that valve, and (*c*) the pulse-shaped output voltage of the differentiating network DN_1 (fig. 5).

Multivibrator

A voltage as indicated in fig. 6*a* can be obtained with the aid of a multivibrator (a set of two valves with the control grid of one coupled to the anode of the other and vice versa, the adjustment being so chosen that current is passed by the valves alternately).

In fig. 5, MV_1 represents the system used in this experimental apparatus. This multivibrator has one valve of the EFF 51 type, containing two pentode systems. A sinusoidal voltage derived from the oscillator *O* (to be described later) is applied to one control grid of this valve (cf. fig. 1); this voltage synchronizes the multivibrator, a multiple of the repetition frequency f_i (about 100,000 c/s) of the pulses obtained being made equal to the fundamental frequency of the voltage v_o that is to be examined. To the other control grid of the valve EFF 51 a voltage v_φ of 50 c/s is applied, which produces the phase modulation of the pulses that is necessary for scanning; this voltage, inter alia, determines the moment at which the current switches over from one pentode system to the other. The amplitude of the 50 c/s voltage is variable, so that the phase sweep of the pulse, i.e. the size of the part of the v_o curve displayed on the screen, can be adjusted.

A portion (R_ψ, fig. 5) of the resistance connected in series with the grid to which the 50 c/s voltage is

fed is made variable for adjusting the mean position of the pulses with respect to v_o, and thus the point of the v_o curve which forms the centre of the oscilloscope waveform.

The working of the pulse generator can be summarized as follows. A multivibrator supplies a voltage showing a step with a frequency of about 100,000 c/s. On being applied to the grid of an EL 6 valve this voltage causes a periodical change of the anode current from 200 mA to zero, thus giving rise to periodical voltage pulses at the output of a differentiating network, the average width of these impulses being in the order of 10^{-8} s. In the mixing circuit the pulses scan the voltage v_o which is being examined.

Synchronization

We now come to the description of the system supplying the voltage for the synchronization of the multivibrator. This voltage has to have a frequency round about 100 kc/s and the fundamental frequency f_o of the voltage v_o to be examined has to be an exact multiple of this frequency.

The voltage in question is derived from an oscillator O (*fig.* 7), the frequency of which is controlled by a reactance valve RT, which is shunted across the oscillating circuit of the oscillator via its anode and cathode and is so connected that, with respect to the oscillating circuit, it behaves as an inductance or a capacitance, the value of which can be continuously controlled by varying its control grid bias [3]).

In order to control the oscillator frequency automatically a device is needed which supplies a correcting voltage to the reactance valve as soon as the oscillator frequency deviates from the right value. This device is built up from elements similar to those we have come across before, namely a mixing circuit M_2 (fig. 7), in which, after having undergone a variable attenuation and a constant amplification, the synchronizing voltage v_{syn} is mixed with pulses generated by a pulse generator I_2, which is likewise controlled by the oscillator O. This pulse generator also consists of a multivibrator (MV_2) followed by an output valve (P_2) with a differentiating network (DN_2) in the anode circuit. This network supplies voltage pulses with a repetition frequency equal to the oscillator frequency. The main difference compared with the pulse generator I_1 previously described is that in I_2 the pulses are not modulated in phase.

The D.C. component of the voltage across the anode resistor of the mixing valve M_2 serves as control voltage for the reactance valve.

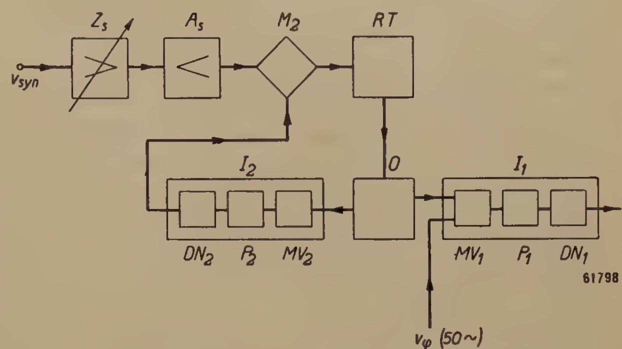

Fig. 7. Synchronization circuit. The oscillator O controls not only the pulse generator I_1 (fig. 1) but also a pulse generator I_2, the pulses from which are mixed with the synchronizing voltage in a mixing circuit M_2. The result is a direct voltage which changes in the event of failure of the synchronization. This direct voltage controls a reactance valve RT which corrects the oscillator frequency when necessary. MV_2, P_2, DN_2: multivibrator, output valve and differentiating network forming the pulse generator I_2, similar to I_1. The externally applied synchronization voltage v_{syn} reaches the mixing valve via a variable attenuator Z_s and an amplifier A_s.

Let us suppose that a multiple of the pulse frequency of I_2 is indeed exactly equal to the frequency f_o of the voltage on the control grid of the mixing valve M_2. The anode current of this valve then consists of pulses equal in amplitude (see fig. 2*b* of article I). As soon as the oscillator frequency begins to change, the phase of the pulses with respect to the said alternating grid voltage is no longer constant; the anode-current pulses of M_2 and thus the control voltage of the reactance valve change in value, so that this valve thereby corrects the oscillator frequency.

The system described here is a special case of what is known as the "I.G.O." system (= *I*mpulse *G*overned *O*scillator) used in transmitters and receivers for synchronizing oscillators. In that system the synchronizing voltage usually has a frequency (from a quartz crystal) higher than the oscillator frequency. In our case it is just the other way round (at most the two frequencies are equal).

The range of synchronization is greater if the amplification in the circuit formed by the oscillator O, the pulse generator I_2, the mixing circuit M_2 and the reactance valve RT is large. When the amplification exceeds a certain threshold value instability arises, as is the case in any regulating system. In order to make the amplification as high as possible without reaching the point of instability it

[3]) The principle of a reactance valve has been described several times in this journal; see, e.g. Philips Techn. Rev. 8, p. 47 (fig. 7) or p. 122, 1946.

[4]) H. B. R. Boosman and E. H. Hugenholtz, Frequency control in transmitters, Communication News **9**, 21-32, 1947.

is necessary to provide, inter alia, for the best possible phase equality, i.e. a tight coupling, between the oscillator O and the pulse generator I_2. This coupling is brought about by means of a diode, so that only the peaks of the sinusoidal oscillator voltage have a synchronizing action upon the pulse generator [5]).

Synchronism ($nf_i = f_o$) occurs when, instead of a continuous strip of light in which nothing can be distinguished, a stationary picture is formed on the screen of the cathode ray tube. When the capacitance in the oscillating circuit of the oscillator is changed it depends both upon the fundamental frequency f_o and upon the amplitude of the synchronization voltage whether isolated or connected synchronization ranges are found for the successive sub-multiples of f_o. When $f_o > 1$ Mc/s one can always find continuous synchronization ranges (and thus the capacitor need not be turned) merely by giving the synchronization voltage a suitable value, which can be done by means of a variable attenuator to be described later (Z_s, fig. 7). If $f_o < 1$ Mc/s then only isolated synchronization ranges occur, which have to be found by turning the capacitor.

Due to the amplifier A_s (fig. 7) a synchronizing input voltage v_{syn} of low value (about 20 mV) suffices. This H.F. amplifier contains one EF 50 valve with a resistor in the anode circuit; at frequencies higher than about 1 Mc/s the amplification rapidly diminishes as the frequency rises, owing to the stray anode capacitance. This is permissible in this case because the higher the frequency f_o of v_{syn}, the closer the sub-multiples of f_o round about 100,000 c/s lie together, so that adjacent synchronization ranges can be obtained with a smaller synchronizing voltage.

The electronic switch

As already noted in article I, the phase modulation of the pulses can be used for producing **two oscillograms simultaneously** by causing the pulses to scan on the return stroke a voltage curve which differs from that scanned on the forward stroke. This greatly facilitates, for instance, measuring of the phase difference between two voltages.

All that is needed for this purpose is an electronic switch, which can be of very simple construction in this case (*fig. 8*). The input voltages v_{oI} and v_{oII}

[5]) For a more detailed treatise on synchronization reference is made to J. M. L. Janssen, A cathode-ray oscillograph for periodic phenomena of high frequencies, Philips Res. Rep., 5, 205-240, 1950 (No. 3).

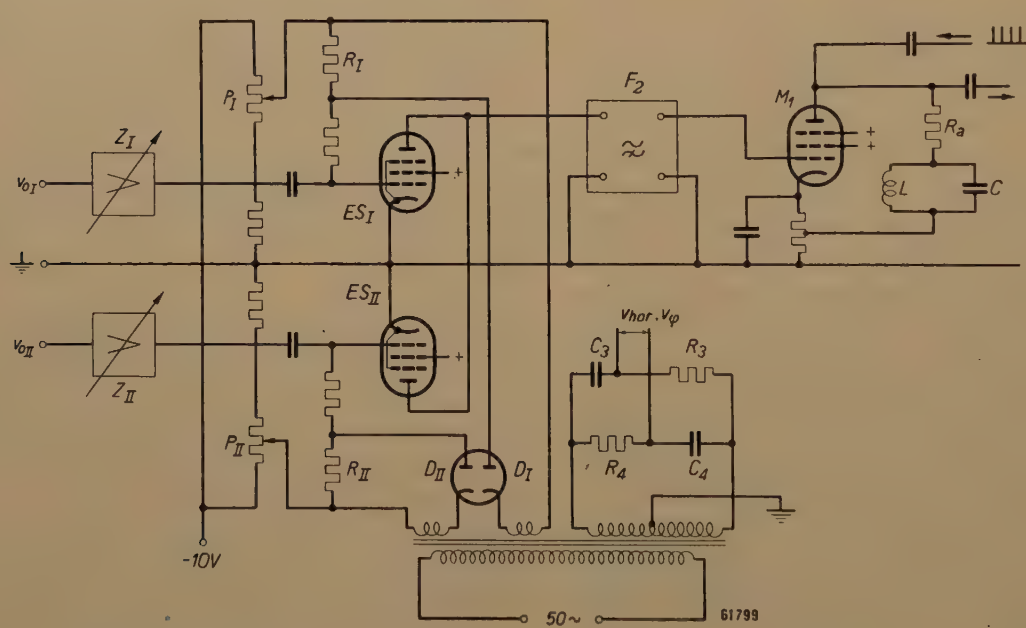

Fig. 8. Electronic switch. The two input voltages to be viewed, v_{oI} and v_{oII}, are fed, each via an attenuator Z_I, Z_{II}, to the input of the valves ES_I and ES_{II} respectively. These valves are alternately blocked by the semi-sinusoidal switching voltages occurring across the resistors R_I, R_{II} via the diodes D_I, D_{II}. The voltage $v_{hor} = v_\varphi$, which brings about both the horizontal deflection and the phase modulation, is shifted 90° in phase in the network C_3-R_3-C_4-R_4 with respect to the alternating voltages, which in turn block the valves ES_I and ES_{II}. P_I, P_{II} potentiometers for adjusting the bias, F_2 high-pass filter; M_1 with R_a, L and C: mixing circuit according to fig. 2. The valves ES_I and ES_{II} are both of the EF 50 type, the double diode D_I-D_{II} is an EB 4 valve.

are fed, via a variable attenuator, to the control grids of the valves ES_I and ES_{II} respectively (both of the type EF 50) in the circuit of the electronic switch. Switching over is done with the mains frequency, at the extreme values of the phase sweep of the pulses. For this purpose the alternating voltage v_φ bringing about the phase modulation is in quadrature with the alternating voltages fed to the electronic switch; the phase shift of 90° is obtained with the aid of capacitors and resistors (C_3, R_3, C_4, R_4).

The electronic switch works as follows. During the half cycle of the mains voltage when the diode D_{II} is conducting the valve ES_{II} is blocked by the voltage across the resistor R_{II}; the diode D_I and the resistor R_I are then non-conducting, the valve ES_I functions normally and the voltage v_{oI} is reproduced on the screen of the cathode ray tube. During the next half cycle the reverse takes place: current flows through D_I and R_I, ES_I is blocked, ES_{II} functions normally and v_{oII} is displayed.

The fact that no rectangular voltages are needed for the blocking of the valves and that semi-sinusoidal voltages suffice is due to the fact that a fairly long time is available for switching over at each peak of the phase sweep, so that the valves need not be cut off suddenly.

Between the common output of the valves ES_I and ES_{II} and the input of the mixing circuit M_1 is a high-pass filter F_2 cutting out any low-frequency voltages arising from the switching.

In addition to the attenuators Z_I and Z_{II}, which are variable in steps and are described below, continuous control is provided in the form of the potentiometers P_I and P_{II}, with which the negative control grid bias of the valves ES_I and ES_{II} can be adjusted.

The connecting cables and the attenuators

When measuring or examining with an oscilloscope voltages with very high frequency components it cannot be left to chance what kind of leads are used for connection to the voltmeter or oscilloscope: in the first place, owing to the capacitance and the damping which lie in parallel with the voltage source when connecting up, the voltage might change considerably, and moreover stationary waves might arise in the lead itself, so that the voltage at one end of the lead would differ considerably from that at the other.

These factors have already been discussed in connection with a millivoltmeter for frequencies up to 30 Mc/s described in this journal [6]). In the case of the oscilloscope described the problem is still more difficult because the transmission along the cable has to be faithful not only in amplitude but also in phase and, moreover, it is desired to extend the frequency limit well beyond 30 Mc/s.

As to the transmission the best solution would be to terminate the cable at the end with a resistance equal to its characteristic impedance. The input impedance of the cable would then likewise be of this value, which, however, would not exceed about 100 ohms and thus would form a very heavy load on the voltage source. In order to avoid this, the cable could be fitted with a "probe" containing an amplifying valve. This valve could be advantageously connected as a cathode follower to match the low impedance of the cable. Furthermore, the probe would have to contain a variable attenuator preceding the valve if voltages are to be examined which, unattenuated, would overload the valve.

Since, among other reasons, our object in building this oscilloscope was in the first place only to verify the accuracy of the principles, we have confined ourselves to fitting an attenuator in the probe, namely a capacitative attenuator. In principle this attenuator — like the one discussed in the article quoted in footnote [5]) — could consist of a variable series capacitor, but in this case the transmission characteristic of the cable would then vary considerably with the value of this capacitor, and thus with the attenuation. For a constant transmission characteristic it is necessary that the input capacitance, viewed from the cable, is constant. This has been achieved by using as attenuator a number of capacitors connected as indicated in *fig. 9*. The voltage to be examined is connected between *0* and *1*, with

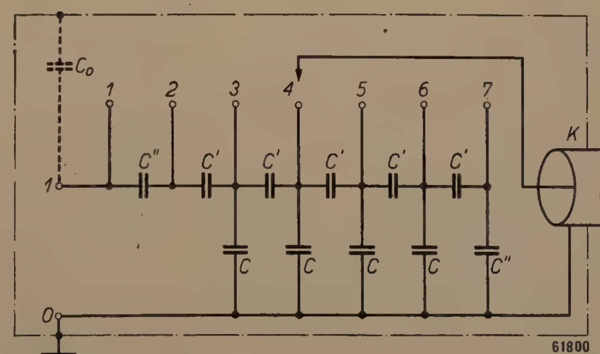

Fig. 9. Network of capacitors acting as variable attenuator, with the property that, with respect to the cable K, it behaves as a capacitance that is independent of the tappings *2 ... 7* to which the cable core is connected (this does not apply for tapping *1*, where the cable is connected directly to the input terminals *0-1*). The capacitances used, whereby the attenuation can be adjusted in steps of $\sqrt{10}$, are: C = 10 pF, C' = 6.6 pF, C'' = 14.6 pF. C_0 is the stray capacitance with respect to earth.

[6]) H. J. Lindenhovius, G. Arbelet and J. C. van der Breggen, Philips Techn. Rev. 11, 206-214, 1949 (No. 7).

the cable core connected to one of the points *1* ... *7*; in this order the attenuation increases step by step by a factor $\sqrt{10}$. Except in the position *1*, where the cable is connected direct to the measuring point and thus the voltage to be examined is transmitted dielectric constant and with the eight capacitor plates made by local plating with silver. A sliding contact runs over silver contact points soldered onto the plates (except the earthed one). The whole is mounted in a probe of small dimensions (*fig. 10*).

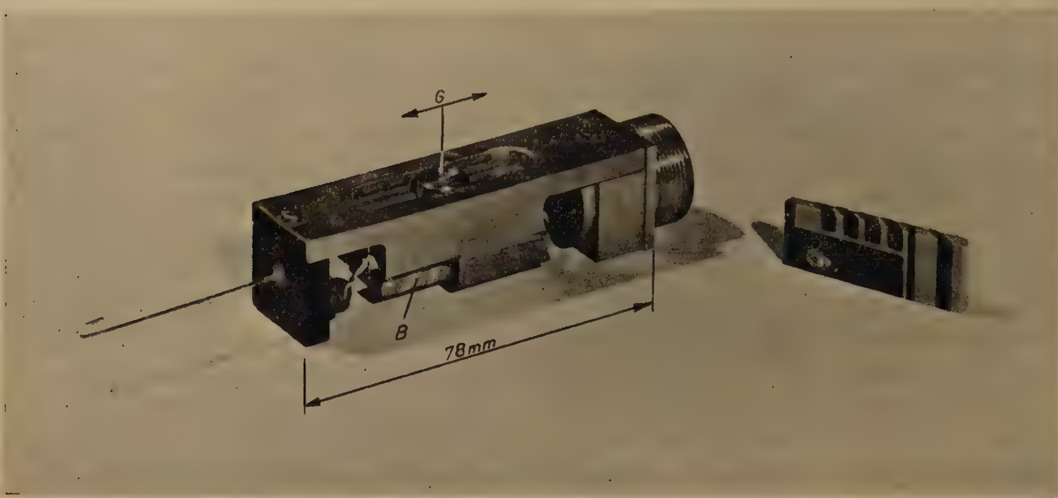

Fig. 10. On the right a block of ceramic material with silver plates together forming the network of capacitors drawn in fig. 9. On the left the complete attenuator (opened); *B* is the ceramic block, *G* the knob of the sliding contact. The right-hand end is connected to the cable; the hooked wire on the left is contacted with the point carrying the high-frequency voltage that is to be examined.

unattenuated, the input capacitance, viewed from the cable, is constant (19.3 pF in the case of fig. 9) and for every step of attenuation the system has the same transmission characteristic.

At 45 Mc/s this characteristic shows a peak, but it has been possible to limit this to 1.25 times the height of the flat part by connecting a damping resistor to the end of the cable. This remaining boosting is favourable in counteracting the decline in sensitivity arising in this frequency range as a consequence of the finite pulse width (see article I).

In order to minimize the input capacitance of the oscilloscope (with cable and attenuator), a cable with a very low capacitance (13 pF per metre cable length) has been used, this being obtained by making it with a core (of tungsten for strength) only 50 μ thick. In the positions *4* ... *7* the input capacitance (between *1* and *0*) is about 5 pF, in the positions *2* and *3* it is somewhat higher, and in position *1* — due to the cable capacitance and the capacitance of the first valve being connected in parallel — the input capacitance is 30 to 35 pF.

The eleven capacitors of the attenuator have been assembled in a convenient shape in the form of a rectangular block of ceramic material with high

Results

A picture of the experimental model of the stroboscopic oscilloscope is given in *fig. 11*, with an explanation of the controls in the subscript.

In *fig. 12* the sensitivity s (deflection on the screen in relation to the input voltage) of the instrument including the cable has been plotted on a relative scale (maximum taken as 1) and also the phase shift α in the cable, both as functions of the frequency. The decline of s at frequencies higher than 30 Mc/s — which without the boosting effect in the cable would be still greater — is due to the finite pulse width. Up to that frequency level the phase characteristic of the cable is practically rectilinear. This limit could be raised to higher frequencies by using a cable terminated with the characteristic impedance, as discussed above.

As a consequence this oscilloscope is of u n i v e r s a l use for examining voltages containing harmonics up to 30 Mc/s. The possibility of "microscopic scanning" is recalled to mind, whereby any part of a cycle can be viewed over the full width of the screen, so that a particular detail can be studied. When one has to do with s i n u s o i d a l voltages — so that no attention need be paid to the phase —

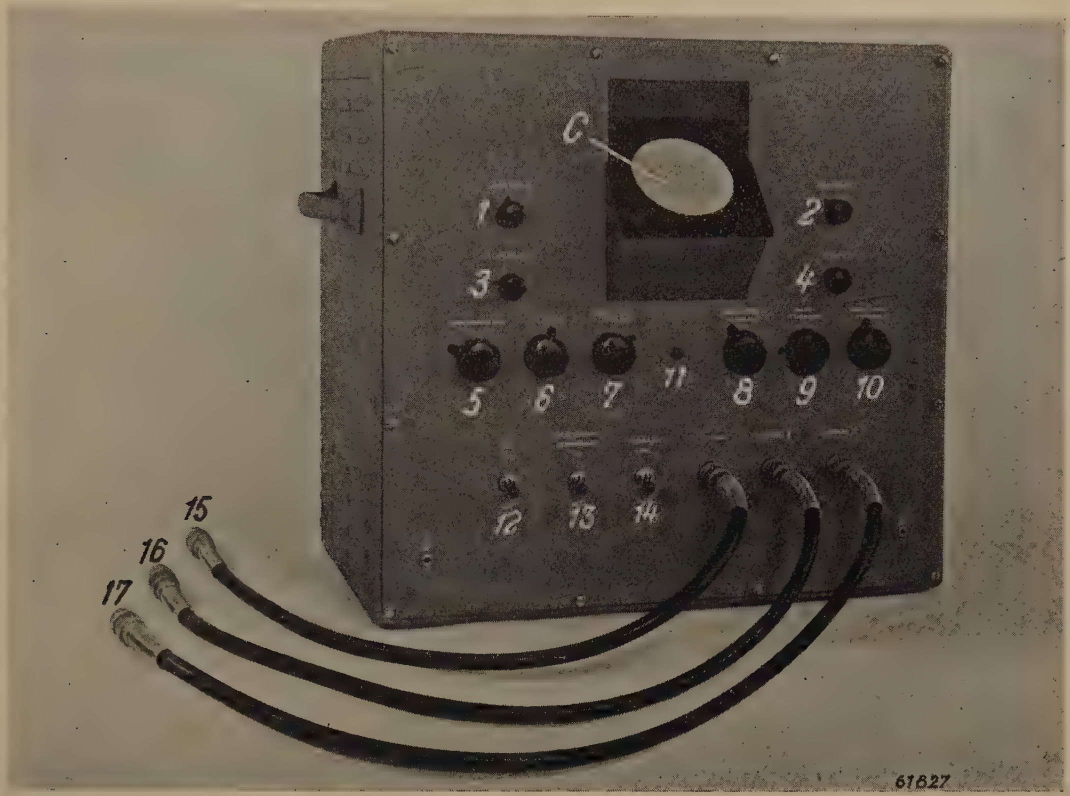

Fig. 11. Experimental model of the stroboscopic oscilloscope. On either side of the cathode ray tube *C* (screen diameter 9 cm) are the knobs *1* and *2* for the horizontal and vertical displacement of the oscillogram, knob *3* for adjusting the brightness (current intensity of the beam) and knob *4* for the focusing. Underneath are the following six controls: *5* adjustment of picture width (amplitude of v_{hor}), *6* synchronization (capacitor of oscillator *O*, fig. 7), *7* size of the part of signal scanned ($\Delta\varphi$, adjustable with the amplitude of v_φ, see fig. 5), *9* selection of the centre of the scanned part (resistor R_φ, fig. 5), *8* and *10* continuous attenuators for the input voltages (potentiometers P_I and P_{II}, fig. 8). *11* is a pilot lamp. At the bottom on the left are three switches: *12* for the mains, *13* for the electronic switch, whilst with *14* any external voltage can be applied as time base. *15*, *16* and *17* are the cables (here without attenuators) for the synchronizing voltage and the two voltages to be examined.

this instrument is still quite useful up to much higher frequencies, namely to about 70 Mc/s, although sensitivity will then be somewhat lower. It can render excellent service in measuring, up to this frequency limit, gain and phase diagrams of amplifiers (for the latter it is only necessary that the two inputs have the same phase characteristic).

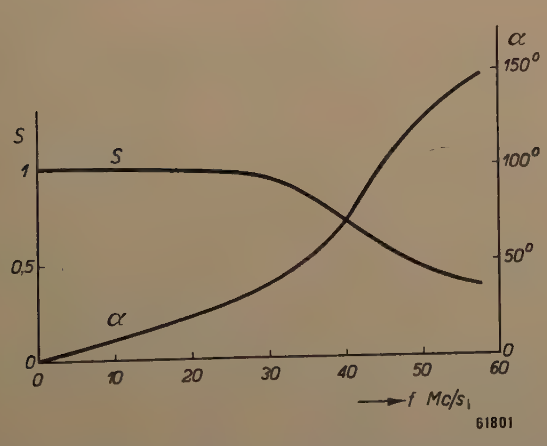

Fig. 12. Relative sensitivity *s* of the complete instrument (including cable) and the phase shift *α* in the cable, as functions of the frequency *f*.

The lower limit of the frequency range for which the oscilloscope can be used is in any case not higher than 1 Mc/s, above which limit, with a synchronization voltage of 20 mV or more, adjacent synchronization ranges are found and the phase sweep of the pulses can be made large enough for scanning more than one cycle if so desired. Between 1 and 0.1 Mc/s however, as already stated, there are isolated synchronization ranges in which the oscilloscope can operate. In that case less than one cycle is scanned; for a larger phase sweep the phase modulation of the pulses would have to be brought about in a more complicated manner than has been judged sufficient for the experimental model, the behaviour of which at high frequencies was of most interest to us.

Finally it is to be mentioned that the maximum absolute sensitivity is about 1 cm picture height per 20 mV (R.M.S. value) voltage.

Summary. A description is given of the principal elements of an experimental model of the stroboscopic oscilloscope, the fundamental principles of which were explained in a previous article. These elements are: the mixing circuit, the low-pass filter and the A.F. amplifier, the pulse generator, the oscillator which, together with the auxiliary circuits, keeps the pulse generator synchronized, the electronic switch which allows of the simultaneous displaying of two signals, the connecting cables and the attenuators. With the oscilloscope described here non-sinusoidal voltages with harmonics up to 30 Mc/s can be reproduced practically undistorted. Details of a non-sinusoidal voltage can be examined over the full width of the screen. Phase and amplitude characteristics of amplifiers, for instance, can be measured up to frequencies of about 70 Mc/s. The sensitivity is about 1 cm picture height per 20 mV (R.M.S.) input voltage.

CONTROLLING THE LUMINOUS INTENSITY OF FLUORESCENT LAMPS WITH THE AID OF RELAY VALVES

by K. W. HESS and F. H. de JONG.

621.327.42:621.3.077.64:621.385.38

Gas-discharge lamps, such as tubular fluorescent lamps, could not hitherto be successfully applied in places where the luminous intensity has to be continuously adjustable within wide limits, as for instance in theatres. Relay valves (thyratrons) however offer a good solution of this problem, a solution which shows the way to new possibilities of application for these lamps.

Controlling the luminous intensity of incandescent lamps

In some cases it is necessary that the luminous intensity of lamps should be continuously variable from the maximum down to a small fraction and vice versa. An example of such a case is the gradual lowering and raising of the lighting in theatres, cinemas and lecture halls and also stage lighting. Further, there are certain systems of show-window lighting and illuminated advertising signs where it is desired to vary the luminous intensity in order to attract attention.

When incandescent lamps are used there are a number of solutions which in essence are very simple. The oldest is the use of resistors, either as series resistors or as potentiometers, for varying the current flowing through the lamps. This method is still largely applied and for small installations provides the solution involving the least initial cost, but for large installations such resistors may be rather expensive, partly on account of the high demands that have to be met in theatres and the like from the point of view of safety against fire. Moreover, the cost of the power lost in the resistors is an item of consideration, at least if the installation has to serve not only for gradually lowering and raising the lighting at the beginning and end of the performances but also for dimming the lighting for long periods.

More economical and much less dangerous, from the point of view of fire risk, are variable ratio transformers [1]) the secondary voltage of which can be varied by means of tappings or a sliding contact running over the turns of the secondary coil. In modern installations this is the solution mostly chosen. The advantages mentioned apply also to induction regulators or rotary transformers and to transductors (D.C. controlled A.C. chokes). The latter possess the additional advantage that they lend themselves well for remote control without the intermediary of mechanical transmissions or servo-motors, an advantage that is particularly of importance for hall and stage lighting installations.

Difficulties encountered in controlling TL lamps

For incandescent lamps these solutions have in course of time been developed to a high degree of perfection. Nowadays we have also tubular fluorescent lamps, which for many applications are to be preferred to incandescent lamps for various reasons. The most important of these reasons are the higher efficiency and longer life of these lamps, further their shape and the spectral composition of the light they produce, allowing of certain decorative effects, and finally the ease with which the small amount of heat generated is carried off. Now how do matters stand when one tries to use these lamps in places where the luminous intensity has to be gradually varied? It is to be foreseen that in the case of fluorescent lamps, through which the current does not begin to flow until a certain voltage — the ignition voltage — has been exceeded, any attempt to vary the luminous intensity, for instance by lowering the voltage, must lead to difficulties which do not arise in the control of incandescent lamps. These difficulties we shall deal with presently, but first attention has to be drawn to a matter which, regardless of the method of control to be employed, presents itself in the case of TL lamps and is related to the fact that, like most gas-discharge lamps, these lamps are fitted with incandescent cathodes. These cathodes are so dimensioned that in normal use they are kept at the right temperature by the discharge itself (ionic bombardment). If, in order to reduce the luminous intensity, the current flowing through the lamp is lowered then the temperature

[1]) Cases where only a D.C. supply is available are left out of consideration here.

of the cathodes drops. This is detrimental to the life of the lamp and moreover, since the ignition voltage is thereby raised, it is not conducive to steady burning. If the luminous intensity — thus the current — of these lamps is to be controlled it is above all necessary to supply heating current to both cathodes, for which purpose a separate filament transformer with two separate secondary coils is needed for each lamp. We shall revert to this point later.

It is understandable that for varying the luminous intensity of TL lamps the known methods developed for incandescent lamps were tried out first, though to little effect, as will be seen from the following.

Let us first take the case of a series resistor. For the luminous flux to be reduced to a certain fraction of the maximum a much larger resistor is needed for a TL lamp than for an incandescent lamp of the same power, because with an incandescent lamp a relatively very small drop in temperature of the filament is sufficient to reduce the luminous flux to a certain extent and this temperature, in turn, rapidly decreases with the lowering of the current passing through the lamp. Consequently a rather small series resistor, say of twice the resistance of the filament in the hot state, suffices to reduce the luminous flux of an incandescent lamp approximately to zero; for a 40 W, 220 V lamp, for instance, about 2500 ohms. In the case of a TL lamp, however, the luminous flux is approximately proportional to the current flowing through the lamp; thus it diminishes only approximately in inverse proportion to the series resistance. In order to reduce the current of a 40 W TL lamp so far as to lower the luminous flux almost to zero the series resistance has to be raised to something like 100,000 ohms, thus many times greater than the series resistance of the corresponding incandescent lamp.

Even if it were possible to overcome this objection of such a large series resistor a difficulty would still be encountered, at least with the TL lamps in their original design, in connection with the high re-ignition voltage of these lamps. To understand how the re-ignition voltage gives rise to difficulties in this connection it is necessary to consider the working of a TL lamp connected in the normal way in series with a choke to an alternating voltage of 220 V (*fig. 1*).

The manner in which the lamp is ignited by a starter has been described previously in this journal [2]). In the stationary state there is an arc voltage of about 110 V across the lamp. The discharge current i, which lags with respect to the mains voltage, passes through zero without remaining at that level a finite length of time. Thus there is no interval of zero current.

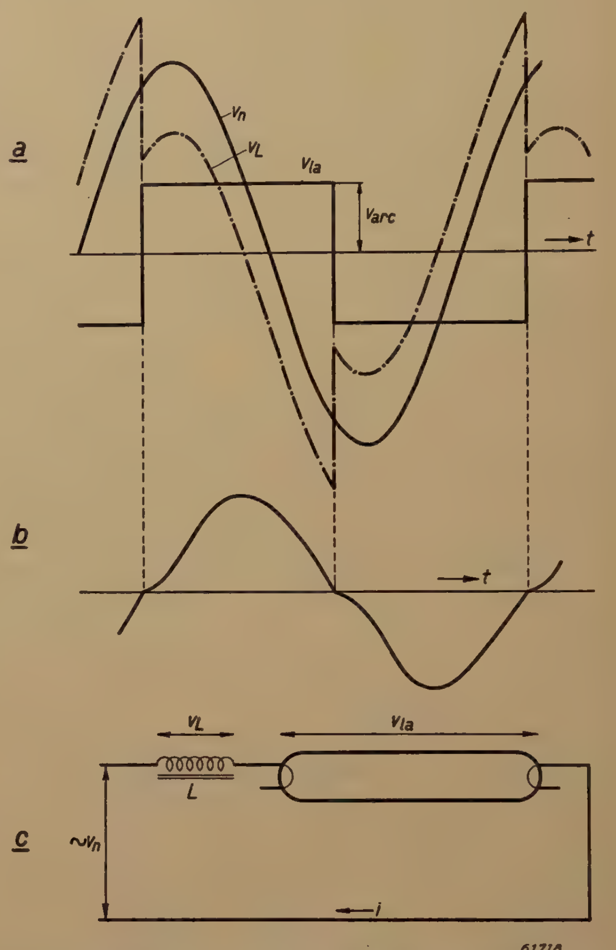

Fig. 1. Voltages and current of a normally working TL lamp (40 W) connected in series with a choke L to a mains voltage of 220 V. Plotted as functions of the time t are: (a) the mains voltage v_n, the voltage v_{la} across the lamp, and the voltage $v_L = v_n - v_{la}$ across the choke, and at (b) the current i. No zero current interval occurs here. v_{arc} = arc voltage. (c) is the circuit diagram. (The curves for v_{la} and v_L are somewhat schematically drawn.)

When the choke is replaced by a resistor the situation is different, for then the current already drops to zero (at $t = t_1$, *fig. 2*) when the mains voltage has fallen to the arc voltage, thus before the mains voltage becomes zero. In the reverse direction the current cannot begin to flow until the mains voltage has changed its polarity and, at $t = t_2$, has reached a level — the re-ignition voltage — which, as we shall presently see, is much higher than the arc voltage. The result is the occurrence of a zero current gap twice in every cycle (also sometimes referred to as the dark period, though during this gap the TL lamp continues to yield some light owing to the after-glow of the fluorescent substan-

[2]) Th. Hehenkamp, A rapid-action starter switch for fluorescent lamps, Philips Techn. Rev. 10, 141-149, 1948.

ces). Now such a gap is undesirable, because the ions present in the lamp at the beginning of a gap rapidly diminish in number owing to recombination, and the lower the ionic concentration the higher is

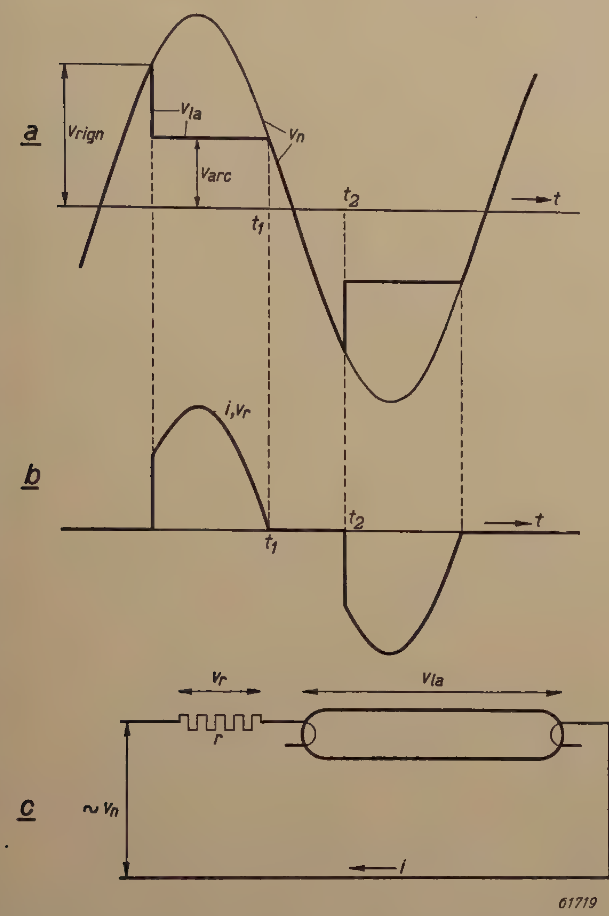

Fig. 2. Voltages and current of a TL lamp connected in series with a resistance r to an alternating voltage of 220 V. v_r = voltage across the resistor; v_{rign} = re-ignition voltage; the meanings of the other symbols are as in fig. 1. Here there is indeed a zero current interval (t_1-t_2).

the re-ignition voltage. In the aforementioned case of a normally working lamp connected in series with a choke, where no such gap occurs, upon the current being reduced to zero the ionic concentration is so great that the re-ignition voltage is but little higher than the arc voltage. With a resistor, however, where a zero current gap always occurs, we have to do with a much higher re-ignition voltage. If, by increasing the resistance, we reduce the current then the arc voltage is raised slightly (a property of the gas discharge in the TL lamp), the zero current gap becomes longer and the re-ignition voltage is raised still higher. With the TL lamps of the old design this increase of the re-ignition voltage may in fact be so great that the lamp does not ignite at all, so that when the luminous intensity of the lamp is reduced there is a risk of the lamp extinguishing, suddenly or after some flickering, and not being able to re-ignite without the help of a starter. Gradual adjustment of the light is then possible only between the maximum luminous intensity and a level that is but little below it. As far as this latter level is concerned there may be great differences between various specimens of the same type of lamp, so that the effect in the lighting of an auditorium would be erratic and unsatisfactory.

The situation is not much better when the lamp is provided with the normal choke (as is desired anyhow in order to avoid dissipative losses while the lamp is burning at full strength) and the variable series resistor is used only for varying the current [3]). At low levels of lighting (large series resistance) the choke has but little effect and the troubles just mentioned still occur.

Much more favourable is the behaviour of the modern type of TL lamps on the market several years already. Thanks to a conducting strip on the glass (to which we shall revert later) these lamps ignite more readily than lamps without this strip. With a series resistance of the order of 100,000 ohms the luminous intensity of such a lamp can indeed be gradually controlled between the maximum strength and a very low level. But this does not mean to say that the problem has thereby been solved. So far we have been considering the case of only one TL lamp, but of course in a hall there is a large number of lamps and one cannot deal with them in the same way as with incandescent lamps by employing one common variable resistor for a large number of lamps connected in parallel. The fact of the matter is that as the number of igniting TL lamps increases after switching on (they do not all ignite exactly at the same instant) the voltage drop in the common resistor increases until ultimately the voltage remaining for the rest of the lamps drops below the ignition level. Each lamp would therefore require its own variable resistor and in a large installation this would complicate matters enormously.

The objections set forth here against the use of series resistors also hold in the case of variable chokes (e.g. transductors) being applied.

As to the other solutions that can satisfactorily be applied with incandescent lamps, these all amount to a variation of the amplitude of the alternating voltage applied (variable ratio transformers, induction regulators, resistors connected as potentio-

[3]) See: The dimming of fluorescent lamps, Electrical Times **115**, 641, 1949 (No. 3001), or Fluorescent stage lighting, Light and Lighting **42**, 169-170, 1949 (No. 7).

meters). If this were to be applied to TL lamps then upon the voltage being lowered the re-ignition level would soon no longer be reached and the lamps would suddenly extinguish.

The foregoing accounts for the fact that hitherto little use, if any, has been made of TL lamps for the lighting of halls and other places where gradual dimming of the lights is desired. The same applies for gas-discharge lamps for high tension (with fluorescence or without, such as neon tubes), which in such cases could otherwise be used to good purpose for decorative reasons.

Control with relay valves

Apart from the methods summed up in the foregoing there is an entirely different way of controlling an alternating current, namely by means of relay valves (thyratrons). These are gas-filled rectifying valves fitted with a control grid. Briefly the working of these valves [4]) amounts to this, that with a positive anode voltage the valve ignites only when the grid voltage exceeds a certain critical value (in general this critical value is a function of the anode voltage.) Once the valve has been ignited the magnitude of the grid voltage no longer has any effect upon the anode current. This current drops to zero only when the anode circuit is broken or, as is always the case in a circuit fed with alternating voltage, when at a certain moment the anode becomes negative.

When the grid of a relay valve is kept sufficiently negative all the time, while the anode circuit is fed with an alternating voltage, then no current at all passes. If the grid voltage is kept continuously above the critical value, or if it is arranged to rise above that level at the moment that the anode becomes positive, then the valve allows current to pass during the longest possible intervals. Assuming, for the sake of simplicity, that there is only a resistance in the anode circuit, then these intervals are approximately half-cycles [5]). Within these two extremes a continuous change is possible by displacing the instant of ignition within such a half-cycle. This can be arranged, for instance, by having a grid voltage consisting partly of an alternating voltage that can be changed in phase with respect to the

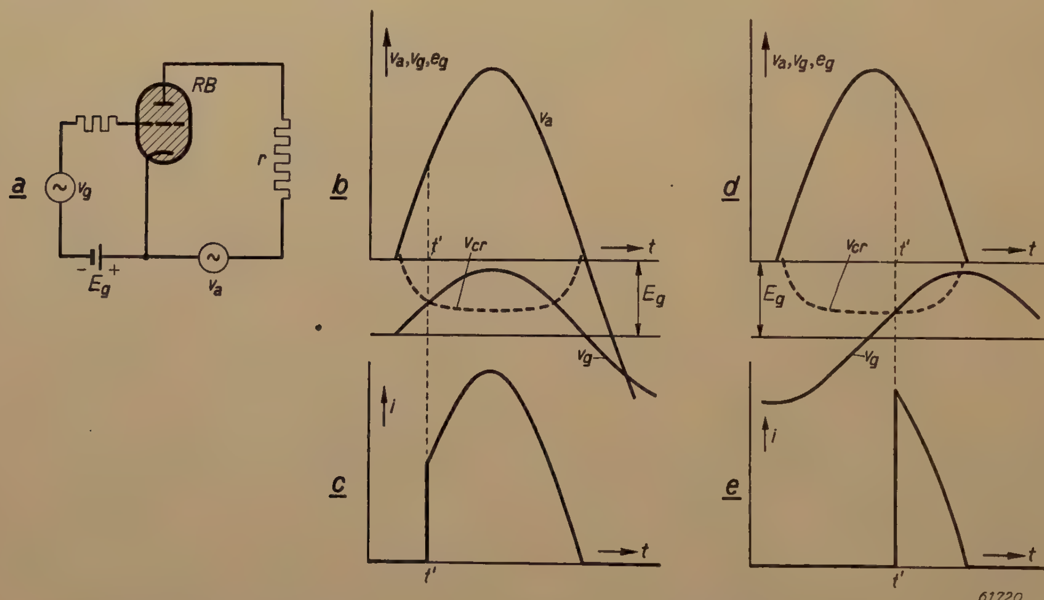

Fig. 3. *a*) Relay valve (thyratron) *RB*, of which the A.C. grid voltage v_g can be shifted in phase with respect to the A.C. anode voltage v_a. The valve is loaded with a resistor *r*. E_g = grid bias. *b*) Early ignition owing to v_g being in phase with v_a. The waveform of the critical grid voltage v_{cr} corresponding to v_a is indicated in broken lines. *c*) Corresponding anode current. *d*) Late ignition, owing to v_g lagging in phase with respect to v_a. *e*) Anode current corresponding to (*d*). *t'* is the moment of ignition.

[4]) See, e.g., D. M. Duinker, Relay valves as timing devices in seam-welding practice, Philips Techn. Rev. 1, 11-15, 1936, or J. W. G. Mulder and H. L. van der Horst, A controllable rectifier unit for 20,000 volts/18 amperes, Philips Techn. Rev. 1, 161-165, 1936.

[5]) Only approximately, because in the first place there is a certain minimum ignition voltage, in consequence of which the valve cannot strike exactly at the beginning of the half cycle, and in the second place owing to the voltage dropping below the arc voltage the valve extinguishes just before the end of the half-cycle. These points, however, are of no consequence here.

anode voltage, as is demonstrated in *fig. 3*. In the case considered here (a load consisting only of a resistance) the anode current assumes the shape of a cut half-sine.

In the foregoing only one half-cycle of the alternating voltage supply has been used. In order to make use of both valves two relay valves are connected in anti-parallel or back-to-back (*fig.* 4), with the two alternating grid voltages in anti-phase.

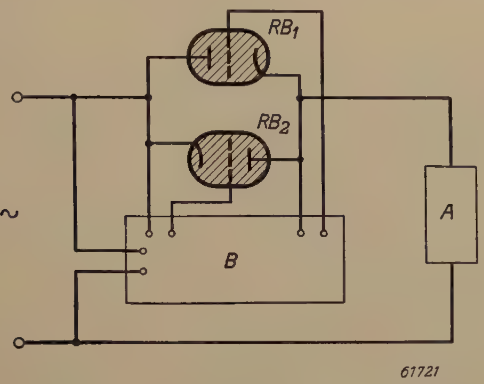

Fig. 4. Control device for alternating current with two relay valves (RB_1, RB_2) connected in anti-parallel. A is the apparatus controlled, B the system with which the moment of ignition of the valves can be adjusted.

Such control devices — which in essence are synchronous switches — have found an important application in electrical welding (both spot and seam welding), often for powers up to several hundreds of kVA. They may also certainly be of use for controlling the luminous intensity of incandescent lamps (with the advantage of easy remote control). But such a control system with the aid of relay valves particularly offers a good solution of the problem with TL lamps, for which no satisfactory method of control had hitherto been found. At first sight one would not expect this system of control with relay valves to be successful with TL lamps, for there is no doubt at all about the occurrence of zero current gaps in this case [6]). Furthermore, in one respect the control device with relay valves shows some analogy with the variable ratio transformer: if we call the quantity $\omega t' = \beta$ the ignition angle ($\omega = 2\pi$ times the mains frequency; t' = the instant of ignition) then in the part of the control range where the ignition angle lies between 90° and 180° the highest instantaneous value of the voltage at the lamp is generally less than the peak V_{max} of the mains voltage, namely $V_{max}\sin\beta$; if β approaches close enough to 180° this voltage ultimately becomes so small as to be insufficient for the ignition of the TL lamps.

On closer investigation, however, it is found that the position is not by any means so unfavourable as one might expect from the foregoing. When modern TL lamps are used and a simple measure is applied to which we shall revert presently, the working may even be said to be most satisfactory.

For an understanding of what is meant we have to explain what takes place in a system as illustrated diagrammatically in *fig. 5*. As soon as the grid voltage in one of the relay valves exceeds the critical value that valve ignites. Current then begins to flow through R_0, a resistor of the order of 10,000 ohms. The TL lamps (only one is drawn in the illustration) are connected in parallel to R_0, each in series with the usual choke. If the lamp and the choke were connected to the mains direct then we should have a (somewhat distorted) alternating current (fig. 1) lagging about 60° with respect to

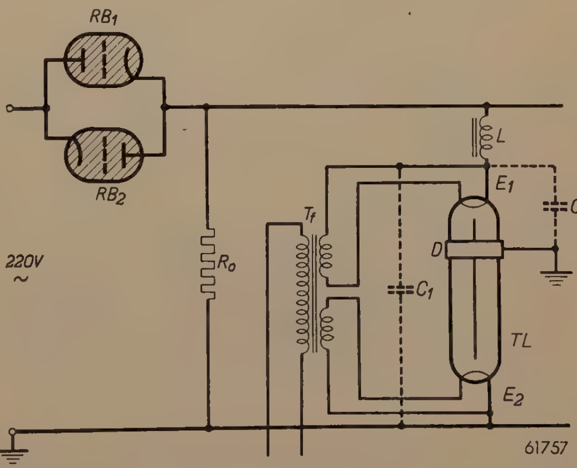

Fig. 5. Relay valves (RB_1, RB_2) used for controlling the luminous intensity of a TL lamp (TL). L = choke in series with each lamp, T_f = filament current transformer. In the middle of the lamp is the conducting strip along the glass tube, earthed via the clamping band D. For the meaning of R_0, C_1, C_2, E_1 and E_2 see the text.

the mains voltage. When, with the system according to fig. 5, the ignition angle β is adjusted to about 60° then the normal current flows through the lamp (the small voltage loss in the relay valves — the arc voltage — may be disregarded here). Upon the ignition angle being enlarged the current decreases, the extreme limit being reached at a value of about 1 mA per TL lamp. The ignition angle is then about 135°, so that at the moment of

[6]) This is not so evident as might appear from fig. 3. This diagram has been drawn for the case where the load is resistive. If there is also inductance in the circuit then under certain circumstances part of the control range may be free of zero current intervals. If the ignition is made to take place gradually later in the cycle then there is always a point beyond which a zero current interval occurs. In the case of a TL lamp with the normal choke the conditions are such that this point is reached very soon. To a good approximation it may therefore be said that a TL lamp controlled by means of relay valves always works with zero current gaps except at the full strength of current.

ignition the mains voltage still has an instantaneous value of about 220 V, which is not very far below the ignition voltage of a TL lamp with hot cathodes.

The fact that with $\beta = 135°$ the current is so much smaller than the nominal current is due to the presence of the inductance L and the arc voltage v_{arc}. The effect of these two quantities is that with increasing β the current falls much more quickly than it does in a circuit where there is only a resistance, as was assumed in the case of fig. 3.

Furthermore the voltage V_{max} in β, suddenly applied to the resistor R_0 each time one of the relay valves strikes, excites an oscillating circuit. This circuit is formed by the inductance L of the choke and the capacitance C_1 between the electrodes (and the filament-current windings connected thereto) of the TL lamp [7]). As a simple calculation shows, if the damping of this circuit and the stray capacitance of the choke were disregarded then the voltage across C_1 (thus across the TL lamp) would reach a peak value of about twice the amplitude of the mains voltage at the moment of ignition of the relay valve; thus with $\beta = 135°$ a peak value of about $2\ V_{max} \sin 135° = 440$ V. Owing to the causes mentioned, the actual value measured is not so high but still a good deal higher than $V_{max} \sin \beta$. Naturally this is all to the good for the ignition of the TL lamps.

Mention was made earlier of a modern design of TL lamps having a conducting strip. This strip is on the outside of the tube and runs in the longitudinal direction, extending almost to the electrodes. A potential difference between the electrodes is thereby mainly concentrated in the small spaces between each electrode and the end of the conducting strip. Consequently, compared with a lamp not having such a strip, the field strength at the electrodes is much greater and the ignition voltage of the lamp correspondingly lower.

The simple measure that has been referred to as contributing towards a considerable improvement — in the sense that the luminous flux can be further reduced without the lamps being caused to burn unsteadily or extinguish altogether — consists in earthing this conducting strip on the lamps (fig. 5). Between this strip and the non-earthed electrode E_1 we then have the capacitance C_2 instead of the capacitance C_1. The voltage peak is then no longer divided between two spaces but is available for one space (that at E_1). This facilitates ignition to such an extent that the smallest current on which the lamps can still burn steadily actually becomes in the order of 1 mA, thus making continuous control of the luminous intensity possible between the maximum and a very low level [8]). Measurements taken on normal TL lamps of 40 W, fed with a control device to be described later, showed that the lowest level at which the lamps still burn quite steadily is between 1/70 and 1/100 of the maximum level. This is so low that, if complete darkness is desired, one can then even interrupt the current entirely without any annoying drop in luminous intensity. It is to be noted that a large number of TL lamps can be controlled simultaneously with only one pair of relay valves; each lamp has to be connected in series with a separate choke in the usual way. Further, it is evident that no starters are needed. On the other hand, as already observed, filament current transformers are required in order to keep the cathodes at a sufficient temperature when the discharge current in the lamps is reduced; it is advisable to vary the heating current in the opposite sense to the discharge current, because with the full current plus the heating current the cathodes would become too hot.

There are various ways of bringing about this variation of the heating current. For instance, the filament current transformers can be fed from a small variable ratio transformer controlled by the same knob as that with which the device is operated for adjusting the ignition point of the relay valves. It may even suffice to vary the heating current step for step, for instance by arranging for contacts on the spindle of the control knob to switch on and off resistors connected in series with the filament current transformers.

A control device with relay valves is suitable not only for TL lamps but also for tubular fluorescent lamps working at high tension, in which case the device is connected in series with the primary of the high-tension transformer.

We shall first give a description of a control device built for 35 TL lamps, following this up with some details of the relay valves suitable for such an application.

Control device for 35 TL lamps

In *fig. 6* a photograph is given of the apparatus used for controlling the lighting of one of our demonstration rooms. This lighting consists of 35 TL lamps of 40 W. As the photograph shows, the apparatus comprises three parts: a casing in

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[7]) See, e.g., Tj. Douma, Voltage impulses in rectifiers, Philips Techn. Rev. 9, 135-146, 1947. In this article a number of oscillograms are given showing oscillations such as are referred to here.

[8]) A provisional report on this method of control appeared under the title "Fluorescent light dimming control" in Philips Technical Communication, pp 9-13, 1948 (No. 7), published by Philips Electrical Industries of Australia Pty., Ltd,. Sydney.

which the two relay valves, among other parts, are housed; a movable control box and a case containing a simple filter. The filter serves for preventing the oscillations mentioned above interfering with radio reception in the vicinity via the lighting mains.

The main elements of the circuit are represented in *fig. 7* .The manner in which the instant of ignition of the relay valves is varied by means of the variable resistor R contained in the control box will be explained later. The control box contains, further, two switches S_1 and S_2. If complete darkness is required then, after it has been reduced as far as possible, the current is interrupted with S_1. If the full light intensity is needed for some length of time then the control device can be put out of action by shorting it with S_2.

In this demonstration apparatus no provision has been made for varying the heating current.

The grid circuit calls for some explanation. Each grid receives in the first place a negative bias of such a value that the valves could not strike if there were no other voltage in the grid circuit. These grid biases are supplied by two small auxiliary rectifiers, the valves of which (AZ 41) can be seen in fig. 6.

The other voltage referred to is an alternating voltage that is shifted in phase in order to change the moment of ignition. This voltage is not sinusoidal, as is represented in *fig. 8a*, but shows a steep front, in this case in the shape of a peak (fig. 8*b*). Thus ignition always takes place at the moment of the voltage peak, regardless of any changes taking place in the characteristic representing the relation between the anode voltage and the critical grid voltage. In the case of a sinusoidal grid voltage (fig. 8*a*) these changes would cause undesired displacements of the moment of ignition.

The peak shape of curve with a steep front has been chosen because this can easily be produced, for instance, with the aid of a so-called peak transformer, i.e. a transformer with the secondary coil

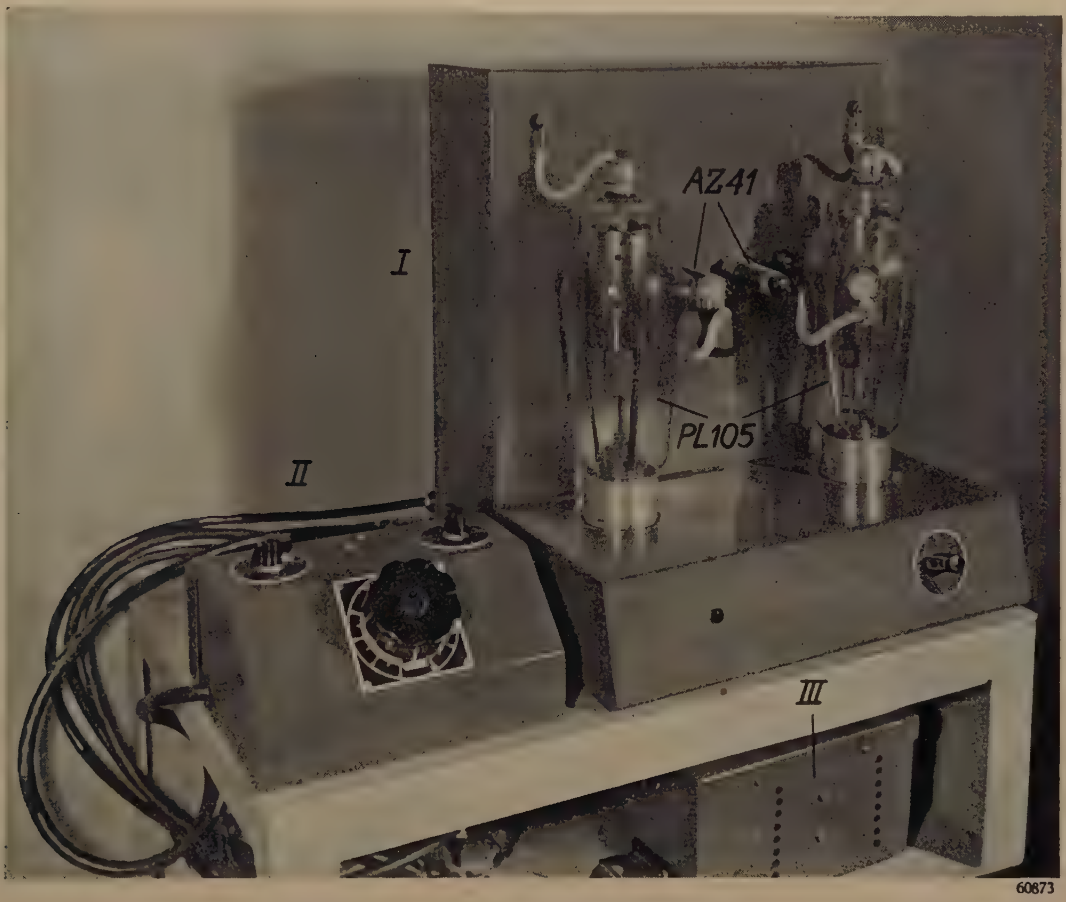

Fig. 6. Control device for 35 TL lamps of 40 W. *I* Opened casing with the two relay valves PL 105. *II* Movable control box. *III* Case with filter preventing radio interference via the lighting mains. The two rectifying valves AZ 41 supply the fixed negative grid bias for the relay valves.

mounted on a part of the core that becomes very highly saturated. *Fig. 9* shows how the core of such a peak transformer can be made. A sinusoidal alternating current passing through the primary coil induces in the said part of the core (K_2, fig. 9) used which reaches saturation at a much lower magnetic field strength than the conventional transformer sheet of which the rest (K_1) of the core is made. This material is an alloy of iron and nickel specially rolled and annealed [9]).

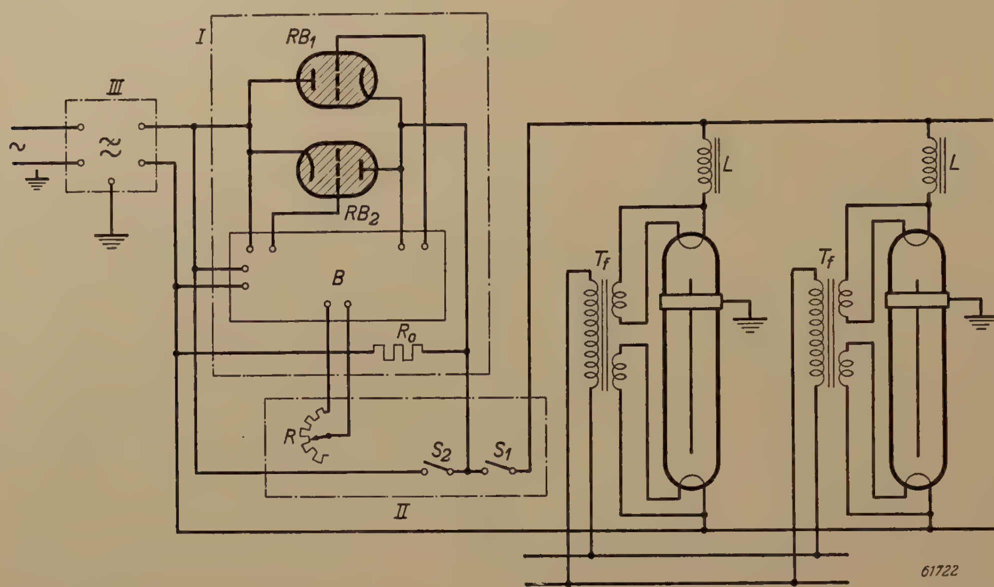

Fig. 7. Basic circuit showing the working principle of the control device illustrated in fig. 6. *I* Case containing the two relay valves (RB_1, RB_2) and the network *B* supplying the grid voltages. *II* Control box containing a small variable resistor *R*, with which the moment of ignition of the relay valves is varied, and two switches (S_1, S_2). L = chokes connected in series. T_f = filament-current transformers. *III* Mains filter.

a magnetic flux density *B* which, as function of the time *t*, has practically the shape of a "square sine" (*fig. 10*). Every time *B* changes in sign a voltage peak is induced in the secondary coil and the quicker *B* changes the steeper are the flanks of that peak. Since peaks with very steep flanks are desired in order to get a sharply defined moment of ignition, for the core part K_2 a material has been

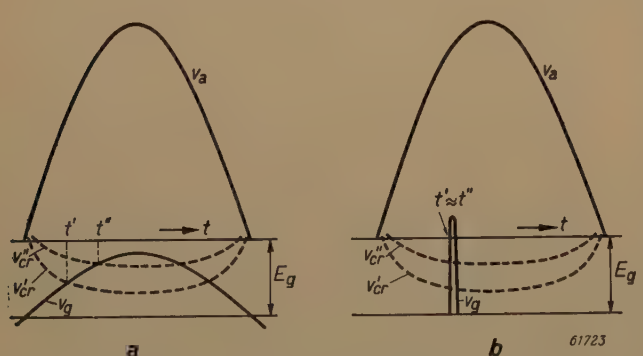

Fig. 8. Any variation in the characteristic of a relay valve, in the case of a sinusoidal alternating voltage on the grid (*a*), influences the instant of ignition ($t' \neq t''$). If, on the other hand, a positive peak-shaped grid voltage is used (*b*) a variation of the characteristic has no such influence and the moment of ignition remains practically constant ($t' \approx t''$).

For shifting the phase of the peaks the mains voltage is applied to a centre-tapped auto-transformer (*fig. 11a*), and to a fixed capacitor *C* and a variable resistor *R* (the resistor in the control box, fig. 7) connected in series. When *R* is increased from 0 to the maximum value R_{max} the phase difference α between the mains voltage and the voltage *MP* (*M* = centre of the coil *AB*, *P* = common point of *C* and *R*) increases from 0 to $\alpha_{max} = 2 \arctan \omega C R_{max}$ (see fig. 11*b*), where $\omega = 2\pi$ times the mains frequency; the voltage *MP* is constant in amplitude. When the peak transformer described above is connected between *M* and *P* the peaks can be shifted in phase by varying *R*; R_{max} has to be so chosen that the limits between which α can be varied (0 - α_{max}) coincide with the limits between which the peak has to be shifted.

In order to feed a peak voltage to the grids of the two relay valves either two peak transformers

[9]) J. L. Snoek, Magnetic cores for loading coils, Philips Techn. Rev. 2, 77-83, 1937, in particular fig. 4, curve *A*. The design of the peak transformer described is due to D. M. Duinker and J. L. Snoek of Philips Research Laboratory.

can be used or one such transformer with two separate secondary windings mounted on the saturated part of the core.

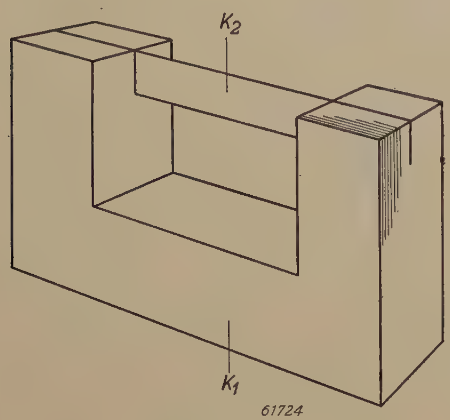

Fig. 9. Core of a peak transformer. K_1 part of the core made of the usual transformer sheet, carrying the primary windings. K_2 part of the core of a much smaller cross section and preferably made of an easily saturated material. The secondary coil is wound on K_2.

When current is taken off between P and M (fig. 11a) $\alpha_{max} < 2$ arc tan ωCR_{max}, so that R_{max} has to be greater than (tan $\frac{1}{2}$ α_{max})/ωC. Therefore, in order to keep R_{max} as small as possible, it is necessary to limit this current consumption to the utmost. Now the primary current of the peak transformer is for the greater part reactive, so that it can be compensated with a suitable parallel capacitor (C_3, *fig. 12*). In this way it has been possible to manage with a variable resistor of very small dimensions.

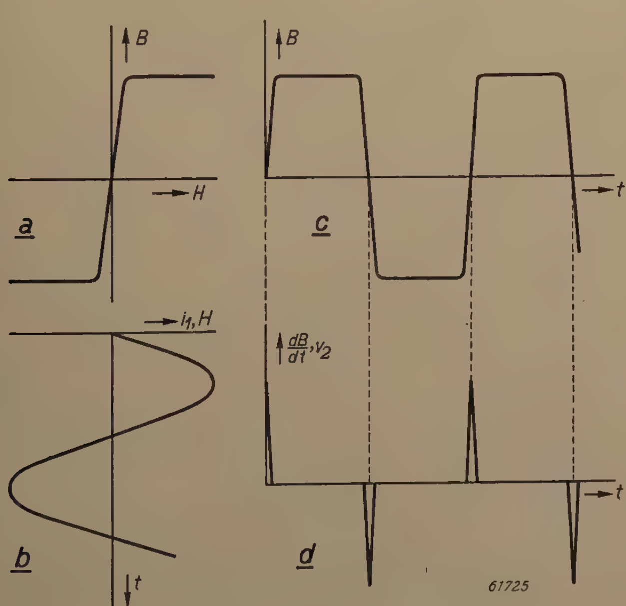

Fig. 10. Illustration of the operation of a peak transformer. a) Flux density B as a function of the magnetic field strength H for the part K_2 of the core (see fig. 9). b) H, proportional to the primary current i_1, as a function of time. c) B as a function of time. d) The voltage v_2, induced in the secondary coil, as a function of time. v_2 is proportional to dB/dt.

Another point to be noted is the following. The circuit is so arranged that the earliest ignition (maximum luminous intensity) takes place at $R \approx 0$. The corresponding moment of ignition is determined by the given amplitude of the mains voltage, the arc voltage and the re-ignition voltage of the TL lamps; it lies at about 60° beyond the zero point of the mains voltage. Now, as fig. 10 shows, the peaks occur when the primary current of the peak transformer passes through zero, so that at $R \approx 0$ this current must have a very definite phase shift with respect to the voltage of the mains from which the TL lamps and the coil AB (fig. 11a) are fed. This fixed phase shift has been provided for by connecting a capacitor (C_4, fig. 12) in series with the primary of the peak transformer.

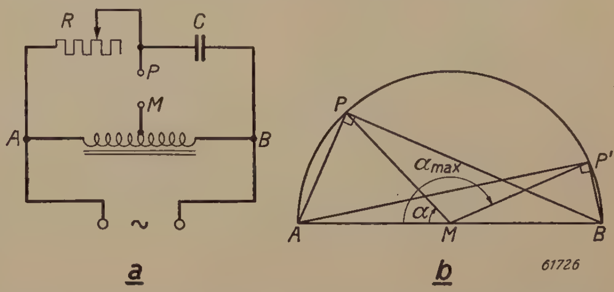

Fig. 11. a) Variation the resistor R causes a change in the phase displacement α between the voltage MP and the mains voltage AB, while MP remains constant in amplitude (M is the centre of AB), as shown by the vector diagram (b). AP corresponds to the voltage across R, BP to that across the fixed capacitor C. At the maximum value of R the point P comes to lie at P', corresponding to the maximum phase shift α_{max}.

The number of TL lamps that can be connected to one pair of relay valves is limited by the maximum permissible mean current for the valves. For the PL 105 type of valve used in the control device described here this current is 6.4 A (per valve). When burning at full strength each 40 W TL lamp demands about 185 mA from the mean current of each of the relay valves, so that with two PL 105 valves at most 6.4/0.185 = 35 TL lamps of 40 W can be used.

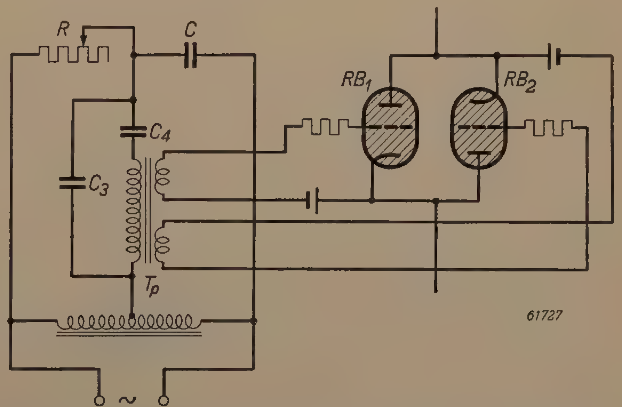

Fig. 12. Details of the phase-shifting and peak-voltage circuits. T_p = peak transformer with two secondary windings supplying a peak voltage to the two relay valves (RB_1, RB_2). R and C as in fig. 11a. C_3 capacitor for compensating the reactive current of the circuit C_4-T_p. C_4 capacitor for giving the peaks the right phase, at $R \approx 0$, corresponding to the full luminous intensity.

Usually the current rating of a TL lamp is expressed by the R.M.S. value, and for the 40 W type this is 420 mA. To derive from this figure the required demand from the mean current of the relay valves we assume that the control device is connected to only one TL lamp burning at full strength and presume, for the time being, that the current flowing through the lamp is purely sinusoidal and thus has a form factor $\pi/2\sqrt{2} = 1.11$. Taking this current to be commutated, its mean value would therefore be $420/1.11 = 378$ mA. Each of the relay valves allows only a half-cycle of this current to pass at a time and therefore its current has a mean value of $\frac{1}{2} \times 378 = 189$ mA. Owing to the deviation from the sinusoidal form (see fig. 1*b*) the form factor is slightly larger and thus the mean current slightly less (185 mA).

In large halls, where usually far more than 35 lamps are needed, it is best to divide the lamps into three groups of at most 35 and to feed each group from a different phase of the mains. Each group is fed via one pair of relay valves; if desired, these three pairs can be controlled simultaneously with only one knob.

Some details of the relay valve PL 105 and similar types

Since the PL 105 type of relay valve used in this control device has never been described in this journal, this opportunity is taken to say something about it.

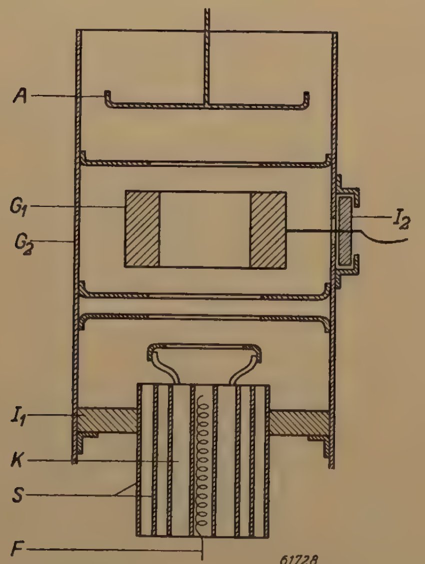

Fig. 13. Cross section of the electrode system of the relay valve type PL 105. K = cathode indirectly heated by the filament F. S = screens for heat insulation. G_1 = control grid, G_2 = screen grid, A = anode. I_1 insulating plate fixing the screen grid with respect to the cathode. I_2 one of the three insulators by means of which the control grid is fixed to the screen grid.

The PL 105 valve has four electrodes (see the cross-sectional drawing in *fig. 13*): an indirectly heated oxide-coated cathode, a control grid, a screen grid and an anode. The gas filling consists of saturated mercury vapour.

The cathode is formed by two concentrical cylinders connected by some radial partitions. The heating filament is inside the smaller cylinder. The surfaces taking part in the emission are the inside of the large cylinder, the outside of the small one and the two sides of the partitions. Enveloping the larger cylinder are two non-emitting cylinders acting as heat insulators so as to minimize the filament current required to keep the cathode at the right temperature. The filament, the cathode and the screen grid are connected to the pins of the valve base via a glass pinch.

The control grid is a graphite ring connected by a flexible wire to a chrome-iron contact cap fused air-tight onto the side of the glass bulb.

The anode is a metal disc with its edge rounded off so as to avoid excessive field strengths. It is connected to a terminal cap (likewise of chrome-iron) on top of the bulb.

The screen grid consists of metal walls with a central opening, mounted between the cathode and the control grid and between the control grid and the anode, and further a metal can enveloping all the other electrodes. The purpose of the screen grid is to shut out all external stray fields and to keep the capacitance between anode and control grid as small as possible with respect to the capacitance between control grid and cathode. The object of the latter is to prevent a sudden change in the voltage on the anode causing the control grid vol-

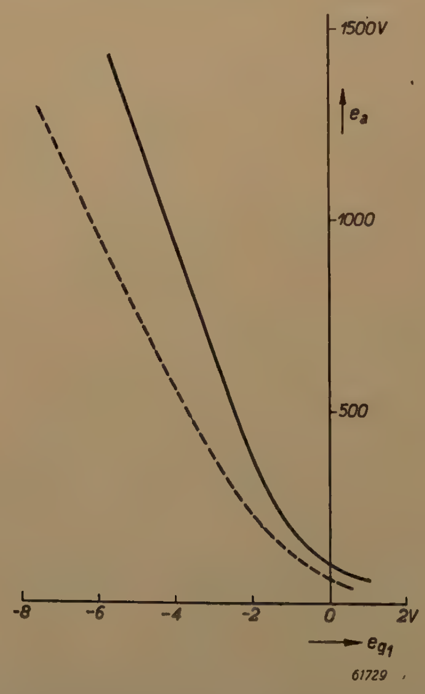

Fig. 14. Average characteristic of the relay valve PL 105; e_a = anode voltage, e_{g1} = control-grid voltage at which the valve just strikes. Fully-drawn line: with screen-grid voltage zero. Broken line: with a certain, positive, screen-grid voltage.

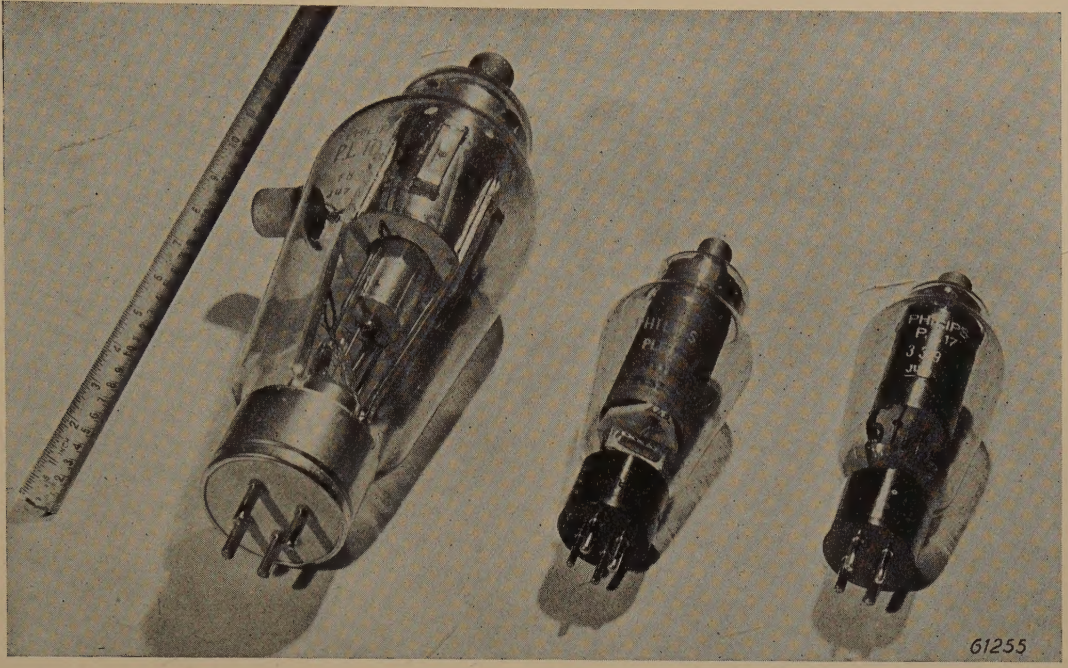

Fig. 15. Three relay valves of similar construction. From left to right: PL 105 (maximum permissible mean anode current 6.4 A), PL 57 (2.5 A) and PL 17 (0.5 A).

tage to exceed momentarily the critical value and thus prematurely igniting the valve. For this purpose the screen grid has to be connected to the cathode across a not too high impedance, say a resistance of 10,000 ohms. For certain applications it is also possible to apply a voltage between the control grid and the cathode: if, for instance, this grid is made positive then with a given control-grid voltage a lower anode voltage is sufficient to cause the valve to strike. The characteristic representing the anode voltage at which the valve strikes, as a function of the control-grid voltage and with a constant screen-grid voltage (*fig. 14*), is thereby shifted to the left. In this way small variations of the characteristic can be corrected.

The characteristic is strongly dependent upon the position of the two grids with respect to each other and with respect to the cathode. These electrodes must therefore be rigidly fixed. The screen grid is fixed with respect to the cathode by the ceramic bottom of the screen-grid can. This can carries three rod-shaped insulators, likewise of a ceramic material, in which the control grid is mounted by means of three radial rods.

The maximum permissible mean current, as already stated, is 6.4 A. Another criterion that may be decisive in certain cases is the peak current, which may not exceed 40 A.

The peak value of the voltage between cathode and anode of the PL 105 valve must not exceed 2500 V, both in the positive and in the negative sense. Otherwise short-circuiting is apt to occur, either — with positive anode — in the forward direction (but at an undesired moment beyond the control of the grid) or in the inverse direction (backfiring), which is always undesirable and, moreover, may be detrimental to the valve.

Two smaller types (*fig. 15*), the PL 57 for a maximum mean current of 2.5 A and the PL 17 for 0.5 A max. mean current, have been developed on mainly the same lines as the PL 105 described here. The PL 57 has an indirectly heated cathode, whereas the PL 17 has a directly heated cathode. These small valves have no screen grid.

Summary. The usual methods for controlling the luminous intensity of incandescent lamps, for instance with the aid of a variable ratio transformer or a series resistor, do not lend themselves for application with TL or other gas-discharge lamps. A good control device for such lamps (on A.C. mains) consists of a pair of relay valves connected in anti-parallel, the ignition point of which can be varied, for instance, by means of a grid voltage that is shifted in phase. A perfectly gradual variation of the luminous intensity of TL lamps between the maximum and a very low value (70 to 100:1) is possible when the conducting strip provided on modern lamps is earthed. To keep the cathodes of the lamps at the right temperature it is necessary that they be heated with a filament current so long as there is no discharge current. For this purpose separate transformers are needed; on the other hand starters can be dispensed with. With this method of control, which lends itself well for remote control, TL lamps can be used also in theatres, cinemas and lecture halls, for stage lighting and other purposes where the luminous intensity has to be gradually lowered or raised. The same applies for high-tension fluorescent lamps. A demonstration apparatus serving 35 TL lamps of 40 W is described. Here the alternating grid voltage is peak-shaped; it is derived from a special transformer and can be shifted in phase by means of a small variable resistor. Some particulars are given of the relay valves employed.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge upon application to the address on the back cover.

1904: J. M. Stevels: Relations entre les structures des verres et leurs propriétés mécaniques, physiques et chimiques (Verres et Refractaires **3**, 359-368, Dec. 1949). (Relations between the structures of glasses and their mechanical, physical and chemical properties; in French.)

Zachariasen's theory (see No. **1774** of these abstracts and Philips Techn. Rev. **8**, 231-236, 1946) concerning network-forming and network-modifying ions in glass and its experimental confirmation by the work of Warren c.s. is treated first. After having discussed the structure of borate glasses (existence of an "accumulation region" and a "destruction region"), the writer indicates certain improvements of this theory. The same ion may, according to circumstances, behave either as a network-forming or a network-modifying iron. According to Smekal the glass network is not only due to an irregular arrangement of oxygen polyhedra but it also depends upon the nature of the bonds within the polyhedra. These bonds can be either heteropolar or homopolar, thereby influencing the distance between the ions involved. The influence of these new conceptions on the interpretation of mechanical, physical and chemical properties of glass is indicated. An important constant, determining the rigidity of the network, is $Y = 2Z - 2R$, where Z is the average number of oxygen ions surrounding a network-forming ion and R is the ratio of oxygen ions to network-forming ions. Y equals the number of bridging oxygen ions per polyhedron. For commercial glasses $4 > Y > 3$, for soft glasses $3 > Y > 2$, whilst glasses with $Y < 2$ show a strong devitrifying tendency. The more rigid the lattice, the more the thermal expansion decreases, whereas the melting point increases.

Finally conclusions may be drawn from the electrical properties of glass as regard its structure and especially as regards the tendency of certain ions to change over from a network-modifying position into a network-forming position.

1905: R. van der Veen: Induction phenomena in photosynthesis, II (Physiologica plantarum **2**, 287-296, 1949).

In this paper (see No. **1882** of these abstracts) induction phenomena experiments on secondary peaks of the adaption curve are discussed. These experiments make it probable that photosynthesis is inhibited by an agent which is formed during photosynthesis and acts with a certain lag of time. The secondary peaks have their origin in this slow action of the inhibitor, which may be O_2 or perhaps some organic peroxide.

Experiments in nitrogen with very little oxygen show that the inactivation of the adaption factor is probably caused by an oxidation of this factor, while its activation may be caused by a reduction by the illuminated chlorophyll complex.

Experiments in pure nitrogen with CO_2 make it probable that the initial CO_2-uptake is damaged in dark under anaerobic conditions, but that recovery takes place when oxygen is present.

Experiments in hydrogen confirm the supposition, made in the first paper, that by heat-treatment of leaves (exposing leaves of Holcus lanatus to 48° C during 3 minutes) the connection between H-donor and chlorophyll is damaged.

1906: H. C. Hamaker: Systematische en toevallige fouten bij het aflezen van de stand van een wijzer op een schaal (Statistica **3**, 209-223, 1949, No. 5/6). (Systematic and random errors in estimating the position of a pointer on a scale; in Dutch.)

Using data published by V. Varangot the writer analyses the systematic and random errors made in estimating the position of a pointer on a scale. At positions between 0.1 and 0.5 and between 0.9 and 1.0 there is a tendency to estimate the position a few 0.01 too low, whereas at positions between 0 and 0.1 and between 0.5 and 0.9 the reverse tendency is evident. In a number of cases the systematic and the random errors are separated by a regression analysis. Personal differences in the magnitude of the systematic errors are investigated. (See No. **1817** of these abstracts.)

1907: F. A. Kröger and W. Hoogenstraaten: The location of dissipative transitions in luminescent systems (Physica The Hague **16**, 30-32, 1950, No. 1).

From the temperature-dependence of the decay of fluorescence in $Cd_2B_2O_5$-Mn and $CdSiO_3$-Mn it is found that the quenching of fluorescence at high temperatures is due to dissipative transitions from the excited state of the centres, whereas the quenching at low temperatures is due to dissipative transitions from higher states of a different character. For the orange samarium fluorescence of $CaWO_4$-Sm the situation is similar, the only difference being that at low temperatures the energy is not dissipated but emitted as tungstate fluorescence.

1908: H. G. Beljers: A demonstration of the induced magnetic moment in the third direction at gyromagnetic resonance (Physica, The Hague **16**, 75-76, 1950, No. 1).

If a material showing gyromagnetic resonance is placed in a constant magnetic field on which an alternating field is superimposed perpendicularly, an alternating magnetic polarization occurs not only in the direction of this alternating field but also in the third direction, perpendicular to both the alternating and the constant field. The existence of this polarisation is proved, using a system of wave-guides (magic tee). (See Philips Techn. Rev. **11**, 313-322, 1950, No. 11, and No. **1850** of these abstracts).

1909: C. J. Bouwkamp: On the freely vibrating circular disk and the diffraction of circular disks and apertures (Physica, The Hague **16**, 1-16, 1950, No. 1).

The writer develops a theory of the acoustic field produced by a freely vibrating, rigid, circular disk on the assumption that the wavelength is large compared to the radius of the disk. The solution is presented in the form of a series of ascending powers of wave number times radius of disk. The new approach, which is based on integral equations, easily permits the explicit calculation of a number of terms of this series. The results are equally applicable to the diffraction at circular disks and apertures of plane scalar waves impinging in the normal direction upon the obstacle. A survey of earlier results by various authors is included.

1910: R. Loosjes and H. J. Vink: Distribution du potentiel dans la couche d'une cathode à oxydes pendant une impulsion de courant de grande densité (Le Vide **5**, 731-738, Jan. 1950). (Potential distribution in the oxide layer of an oxide-coated cathode during a current impulse of high density; in French.)

The distribution of the potential in the coating of an oxide-coated cathode is investigated according to two different methods. Firstly the distance of the anode to the cathode is varied and the measured potential differences are extrapolated to zero distance. In this way the value of the potential at the surface of the coating is found. Secondly the potential distribution in the coating is determined by a probe method. No jump in potential is found at the interface between metal and oxide. The greater part of the potential drop is concentrated near the outer surface of the coating.

1911: W. Nijenhuis: Theoretische grenzen voor de overdracht van brede frequentiebanden (T. Ned. Radiogenootsch. **15**, 13-31, 1950, No. 1). (Theoretical limits for the transmission of broad frequency bands; in Dutch.)

The paper deals with the question of obtaining maximum gain in a given frequency band from two-terminal and four-terminal interstages. It has been attempted to elucidate and, partly, to generalize the treatment in Bode's: Network Analysis and Freedback Amplifier Design.

1912*: E. W. Gorter: L'aimantation spontanée de ferrites ferromagnetiques à structure de spinelle (C.R. Acad. Sc., Paris **230**, 192-194, 1950, Jan. 9). (Spontaneous magnetisation of ferromagnetic ferrites with spinel structure; in French.)

The spontaneous magnetisation of a number of ferrites of the type MFe_2O_4 (M = bivalent metal) and of mixed crystals of these ferrites with zinc ferrite ($ZnFe_2O_4$) is measured; the results confirm Néel's theory (Ann. Physique **3**, 137, 1948).

1913: J. L. Meijering and G. W. Rathenau: Rapid oxidation of metals and alloys in the presence of molybdenum trioxide (Nature, London **165**, 240, 1950, Febr. 11).

The influence of molybdenum trioxide on the oxidation of metals and alloys has been studied as a function of temperature. A graph is given of the depth of penetration in 8/92 Al-Cu wires for different times of heating ($^1/_2$ h, 3 h, 20 h, 165 h) in the temperature range from 400 °C to 550 °C.

The results of these and other experiments support the view that the occurrence of a liquid oxide phase is the determining factor, not the dissociation of MoO_3 as put forward by Leslie and Fontana.

1914: E. J. W. Verwey: Atomic arrangement in spinels in connection with their physical properties (Proc. 11th Int. Congr. Pure and Appl. Chem., Vol. I, 285-291, Febr. 1950).

Survey of investigations regarding the structure and the electrical and magnetic properties of spinels (see Nos **1738**, **1739**, **1845** of these abstracts and Philips Techn. Rev. **9**, 185-190, 239-248, 1947).

1915: K. F. Niessen: On avoiding low frequencies in a rectangular cavity resonator used as part of a triode generator (Appl. sci. Res., The Hague **B1**, 325-340, 1950).

Reprint of an article published on the occasion of the Marconi Congress, Rome 1947 (Roma, Consiglio Naz. delle Ricerche 1948, 312-329). It is shown that by adding a "side room" to a prismatic cavity of quadratic or triangular cross-section (see Nos **1815**, **1853**, **1854** of these abstracts) all lower frequencies except one (the frequency required) are changed. By combining such extended cavities, prismatic resonators are obtained with a symmetrical cross section, in which vibrations with undesired frequencies may be suppressed by applying a bar at a suitable place.

1916: E. J. W. Verwey: Theory of the electric double layer of stabilized emulsions (Proc. Kon. Ned. Akad. Wetensch. Amsterdam **53**, 376-385, 1950, No. 3).

The electrical potential function and the distribution of the charges at the interface of two immiscible liquids are calculated with the aid of a Gouy-Chapman type of theory, for the case that in addition to the original double layer a surface charge is present at the interface.

1917: K. F. Niessen: On one of Heisenberg's hypotheses in the theory of specific heat of superconductors (Physica, The Hague **16**, 77-83, 1950, No. 2).

An assumption made by Heisenberg in Koppe's theory of the specific heat of superconductors is discussed. A comparison with another problem seems at first sight to contradict this assumption but turns out to support it. Heisenberg's assumption is also confirmed in a direct way.

1918: K. F. Niessen: The energy of the normal electrons in a superconductor as a function of temperature and thickness of the superconducting layer on the Fermi surface (Physica, The Hague **16**, 84-94, 1950, No. 2).

In order to simplify calculations Heisenberg's assumption about the superconducting layer covering a part of the Fermi surface (see No. **1917**) is modified in so far that a layer is assumed of thickness Δ (by which is meant the difference of the energies corresponding to the upper and lower surfaces of the layer), which layer, covering a part ω of the Fermi surface, is entirely inaccessible to normal electrons, whilst all its volume elements h^3 are supposed to be occupied by superconducting electrons. A formula for the energy of the normal electrons is derived, which is a function of ω, T and Δ and which for $\Delta \gg kT$ coincides with Koppe's expression in the Heisenberg theory but for $\Delta \ll kT$ is identical with the value well known from Sommerfeld's theory of metals. A relation is derived between the transition temperature and the numbers of superconducting and normal electrons per cubic centimeter, both at $T = 0$.

1919: J. L. H. Jonker: Buizen met lintvormige electronenbundel; contact-, schakel-, kies- en telbuis (T. Ned. Radiog. **15**, 37-52, 1950, No. 2). (Valves with ribbon-shaped electron beam; contact valve, switch valve, selector valve, counting valve; in Dutch.)

Paper covering the subject already referred to under No. **R 126**.

1920: K. S. Knol: Electromagnetische golven in rechthoekige golfpijpen (T. Ned. Radiog. **15**, 53-74, 1950, No. 2). (Electromagnetic waves in rectangular wave guides; in Dutch.)

A survey of wave guide theory is given. The method of Brillouin for rectangular wave guides is dealt with in more detail and the solution of Maxwell's equations in the interior of a wave guide is found by superimposing the incident wave upon three reflected waves occurring when a plane linearly polarized electromagnetic wave strikes against two mutual perpendicular metal walls. Some applications of wave guides in practice are mentioned. A rubber sheet model may be used in studying problems of propagation of TE_{10} waves in rectangular wave guides. (See Philips Techn. Rev. **11**, 156-163, 1949, No. 5.)